NASA TECHNICAL TRANSLATION NASA TT F-16,108

FUNDAMENTALS OF THE SPACE INDICATION OF EARTH RESOURCES

V. V. Andreyanov

(NASA-TT-F-16108) FUNDAMENTALS OF THE SPACE INDICATION OF EARTH RESOURCES (Scientific Translation Service) N75-15136

G3/43 Unclas 07733

Translation of "Osnovy kosmicheskoy indikatsii zemnykh resursov", Academy of Sciences USSR, Institute of Space Research, Moscow, Report D-171, 1974, pp. 1-72.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546 JANUARY 1975

STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TT F-16,108		

4. Title and Subtitle	5. Report Date
FUNDAMENTALS OF THE SPACE INDICATION OF EARTH RESOURCES	January 1975
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
V. V. Andreyanov	10. Work Unit No.
9. Performing Organization Name and Address SCITRAN Box 5456 Santa Barbara, CA 93108	11. Contract or Grant No. NASw-2483
	13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "Osnovy komicheskoy indikatsii zemnykh resursov", Academy of Sciences USSR, Institute of Space Research, Moscow, Report D-171, 1974, pp. 1-72.

16. Abstract

This paper reviews the methods and instrumentation used in satellite reconnaissance of Earth features. The problems of interpreting this information for the different sectors of the economy are not considered herein.

Changes in the electromagnetic spectrum of solar radiation reaching detectors on board satellites are analyzed. Possible methods are given for the recognition of natural features. Requirements for satellites are specified. The principles of operation and the characteristics of photographic and television cameras, scanning radiometers, and active radar methods for the investigation of Earth's resources are briefly discussed. Some of the problems subject to solution in the near future are cited.

17. Key Words (Selected by Author(s))	18. Distribution Statement
PRICES SUBJECT TO CHANGE	Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

TABLE OF CONTENTS

ANNOTATIONS

This paper reviews the methods and instrumentation used in satellite reconnaissance of Earth features. The problems of interpreting this information for the different sectors of the economy are not considered herein.

Changes in the electromagnetic spectrum of solar radiation reaching detectors on board satellites are analyzed. Possible methods are given for the recognition of natural features. Requirements for satellites are specified. The principles of operation and the characteristics of photographic and television cameras, scanning radiometers and active radar methods for the investigation of the Earth's resources are briefly discussed. Some of the problems subject to solution in the near future are cited.

FUNDAMENTALS OF THE SPACE INDICATION OF EARTH RESOURCES

V. V. Andreyanov

Introduction

The increase in the world's population, the progressive destruction of its resources, the pollution and destruction of the environment make it necessary to take measures on a global scale to develop and protect new resources and to improve the effectiveness of their utilization. /3*

One of the most important problems facing science is the protection of the natural environment. The pressing need and importance of solving the common problems of discovery, control, and protection of the natural resources of the Earth, including the environment, is no longer in doubt. The problem facing science now is one of "adjustment between man and nature", of predicting the consequences of the development of current technology, and of the development of methods and means which would improve the existence of future generations.

An important role in the solution of these global problems, many of which do not have national boundaries, will be played by the

*Numbers in the margin indicate pagination in the original foreign text.

space sciences. The first steps have been taken. However, the questions as to what measurements and surveys relying on space technology should be selected, and how these should be performed, have yet to be answered. The manner in which the results of these measurements can be used and the particular combination of conventional and space methods best suited for the various sectors of the economy have yet to be determined.

At present, the feasibility of using space methods and means is being determined both experimentally and theoretically. We are witness to, as well as participants in, the successful, but prolonged development of space sciences in weather forecasting, radiation monitoring, and in radio communications.

The study of the Earth's resources presents a very wide diversity of tasks. An initial classification according to priorities based on human needs is given in Table 1.

This table presents four categories of requirements of a modern society and lists the sectors of the economy and branches of science which serve to fulfill these needs. /5

The fundamental areas of knowledge, such as physics, chemistry, mathematics, and sociology, are related to all four groups. Although, strictly speaking, it is true that the fourth group does not belong to the category of natural resources, it does reflect the needs of humanity. The third column of the table lists most of the characteristics of natural resources which can be controlled or studied.

The most important characteristic of aerial/satellite methods of investigating natural resources is that all measurements and surveys have to be made remotely through the atmospheric layer.

What phenomena permit the remote sensing of the Earth? In general, it is the eigen electromagnetic radiation over a broad range of frequencies; the reflected radiation from the Sun (or from

TABLE 1

Problems		Sectors of economy and branches of science	Subject of investigation
I.	Production of food supplies	Agriculture, fishing and cattle industries, development biology, and meteorology	Soil condition/moisture, salinity, erosion, temperature/appearance, age, degree of maturity, presence of disease, territorial distribution of grass, gardens, meadows, fields; detection of locusts, mosquitoes, and other pests; condition of irrigation and development systems; quantity and migration of cattle, reserves and distribution of fish, algae, and other sea products; reserves and distribution of fresh water.
II.	Production of raw products	Geology, forestry, oceanology, geography	Appearance, age, condition, territorial distribution and wood content of forests; sources, areas and movement of fires; reserves and distribution of ores, oil, gas, coal, construction rock, salts, minerals and other deposits; discovery of subsurface waters/volume and distribution/.
III.	Study and control of the environment	Meteorology, oceanology, water resources, urbanization, biology, geography	Quantity and distribution of solar radiation; degree and character/chemical, mechanical, biological/; air and water pollution; distribution and condition of ice, snow, icebergs; condition of coast line and underwater *; content and distribution of moisture, ozone, carbon dioxide, oxygen, and other atmospheric gases; motion of air and water masses/currents, turbulences, clouds, precipitates, winds/; water level in basins; surface relief and its changes; condition of volcanos.
IV.	Social intercourse, development of people	Culture and education, transportation, communications (on Earth, space) geography, navigation	Distributionof settlements, planning of cities and transportation links; condition of ionosphere/influence on radiocommunications/ magnetosphere/influence on communications and navigation/.

*Translator's note — missing Russian word in original foreign text.

artificial radiation sources on space stations); and magnetic and gravitational fields. The investigation of the relationship between the parameters of these radiations and fields and the characteristics of minerals, rocks, seas, forests, atmosphere, and other resources is one of the basic scientific problems in the study of natural resources from space.

Figure 1 represents a schematic representation of the remote sensing of characteristics of objects on the ground. Current methods and means of measurments are especially successful in the detection of electromagnetic emissions. Therefore, artificial Earth satellites (AES) are equipped with instrumentation primarily sensitive to these emissions.

The primary advantages of studying natural resources from orbiting AES in comparison with traditional ground methods include: the investigation of large territories and large bodies of water (a single frame from an Earth satellite will cover an area of 10 - 50 thousand square kilometers, with a resolution at the surface of 100 - 200 meters); the simultaneous study of the surface and of the atmospheric layers at various heights; the determination of the relationship between various phenomena occurring in different regions of the Earth; the systematic observation of the development of natural phenomena, especially important for the more inaccessible regions of the Earth; and, the collection of information from air, sea, and ground measuring probes and platforms concurrently with the performance of remote sensing. It should be noted that AES, in orbits at altitudes of over 200 - 300 km, may be able to operate for prolonged periods (1 - 3 years), regardless of the seasons, weather conditions, and other ground factors.

On the other hand, the realization of these potentials entails a number of difficulties. The data on natural resources is of an indirect nature. The range of frequencies suitable for the study of the Earth's surface includes only the visible range (0.4 - 0.7 microns), the ultraviolet and infrared windows (0.2 - 0.4; 0.7 - 2.4;

3 - 5; 8 - 15 microns), and part of the radio range (fractions of a centimeter to tens of meters). These limitations are imposed by the atmosphere. It is also necessary to take into account the influence of the atmosphere in the entire optical range. The motion of the AES and the diurnal and annual motion of the Earth must be considered as well. As a result, the remote sensing of natural resources from space became feasible only due to progress in the space sciences, and in the technology and methods of data processing.

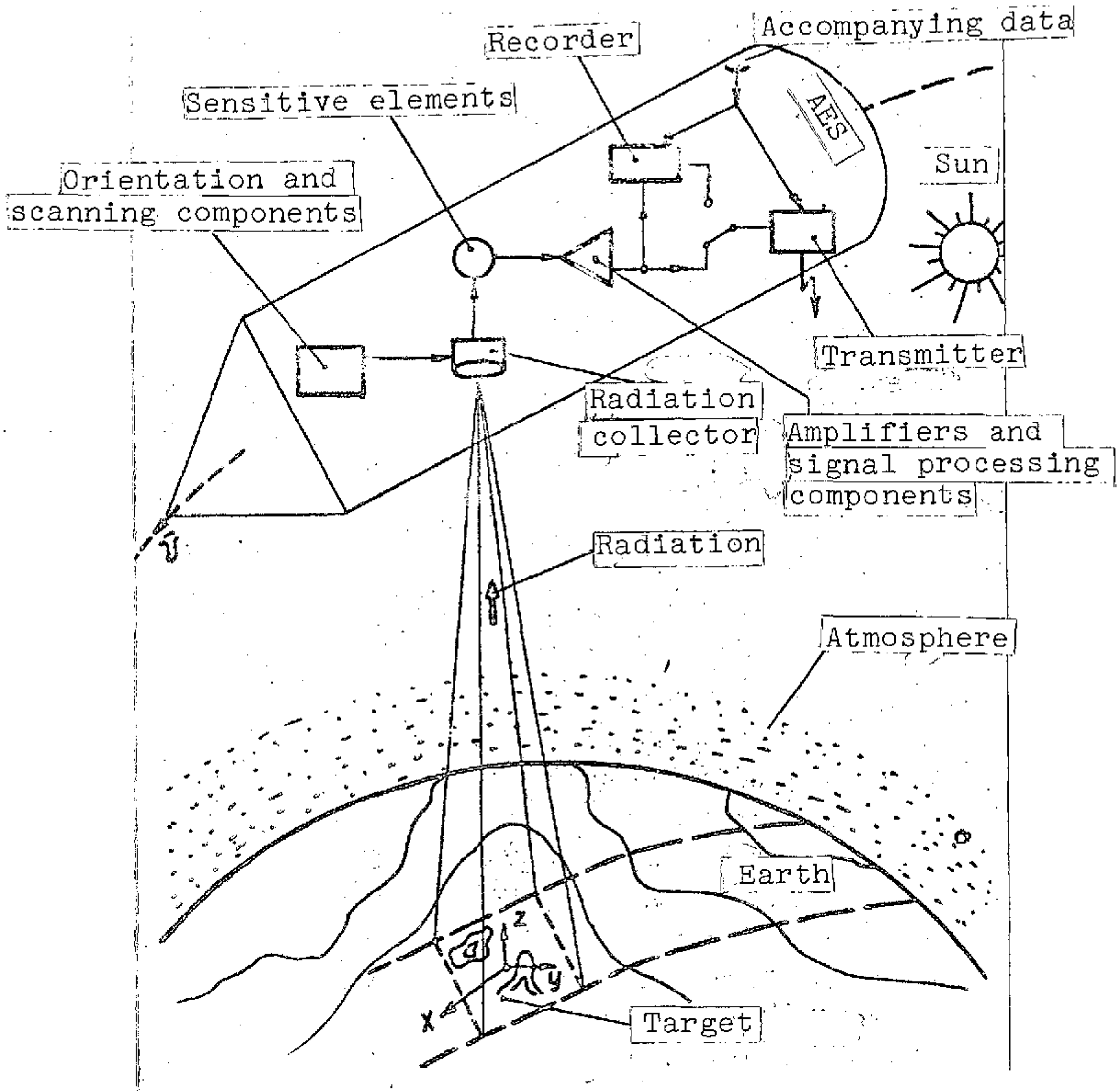


Figure 1

Reflected and Emitted Radiation from the Earth

The short wave portion of the electromagnetic radiation from /8 the Sun (approximately up to 0.3 microns) is scattered or absorbed even by the uppermost layers of the atmosphere, while radio wavelengths longer than 20 - 30 meters are stopped by the Earth's ionosphere. Therefore, only the part of the solar spectrum between 0.3 microns and 20 meters can penetrate the atmosphere. In this portion of the spectrum (from the near ultraviolet to the radio range), the energy is distributed very nonuniformly; 95% of all the energy of the solar radiation is contained in the range from 0.3 - 2.4 microns, that is, in the visible, near ultraviolet, and infrared portions of the spectrum. The maximum in the energy spectrum corresponds approximately to 0.5 microns, in the yellow-green portion of the spectrum. The energy of solar radiation carried by the radio wavelengths is infinitely smaller, and corresponds approximately to 10^{-12} of the energy in the visible range.

The penetration of the Sun's radiation to the surface of the Earth is accompanied by the following processes:

— absorption,
— scattering,
— refraction,
— addition of eigen radiation from the atmosphere to the solar radiation.

In the radio wavelength portion of the spectrum, sharp absorption peaks lie in the range of 22, 60, 110, 200, and 300 GHz.

The atmosphere partially absorbs the radiation in the visible and near infrared regions of the spectrum. Solid and liquid particles (aerosols) dispersed in the atmosphere scatter the incident radiation. The most strongly absorbed wavelengths lies in the range of 2.4 - 3, 5 - 8, and above 14 microns. The visible portion, the most intense one of the spectrum, penetrates well to the Earth's surface, despite the action of the atmosphere. Since the natural formations studied most frequently from AES (with the exception of extended targets) are seen against a background of surrounding objects, then the degree of discrimination in many cases is determined by the contrast. Scattered radiation from the atmospheric aerosols decreases contrast. The intensity of scattering depends on the ratio of the aerosol particle size (ζ) and the wavelength of radiation (λ). Haze particles are very small: the radius is smaller than 0.5 microns; fog and clouds contain droplets or ice crystals with radii between 1 - 100 microns. In addition, fog comes into contact with the Earth's surface. Rain drops have radii between 0.25 and 3 mm. Thus, haze scatters visible radiation (when $\zeta \approx \lambda$), but transmits infrared. Fog and clouds scatter both visible and infrared. Only radio wavelengths are not scattered by atmospheric aerosols. /9

A consequence of atmospheric refraction is the change in the direction of propagation of the radiation as it passes through optical and temperature inhomogeneities of the atmosphere.

On reaching the surface of the Earth, the solar radiation is partially reflected and partially absorbed. The reflected portion of the energy, once it passes through the atmosphere again, can be detected by satellite instrumentation. The transformation process of the solar radiation can be graphically represented as in Figure 3.

Cloud cover makes it impossible to see the surface of the Earth in the optical range, due to the intense background of scattered radiation, as well as due to absorption. On a global scale, the Earth reflects less than 10% of the energy reaching it from the Sun.

Thus, with an energy flux in the visible and infrared regions beyond the atmosphere's boundary equal to approximately 0.14 W/cm^2, only 0.07 W/cm^2 reaches the surface, and only 6.4 mW/cm^2 is reflected. However, average figures are useful only in the evaluation of the Earth's energy balance, and not for calculating remotely sensed objects.

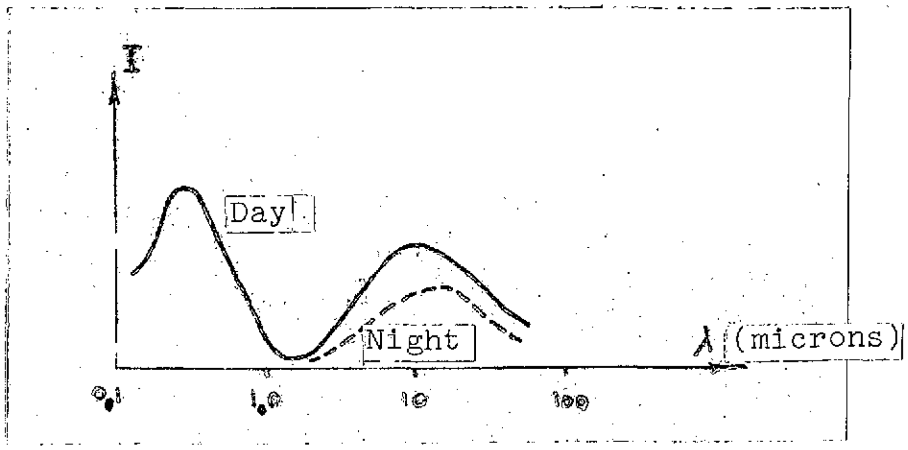


Figure 2

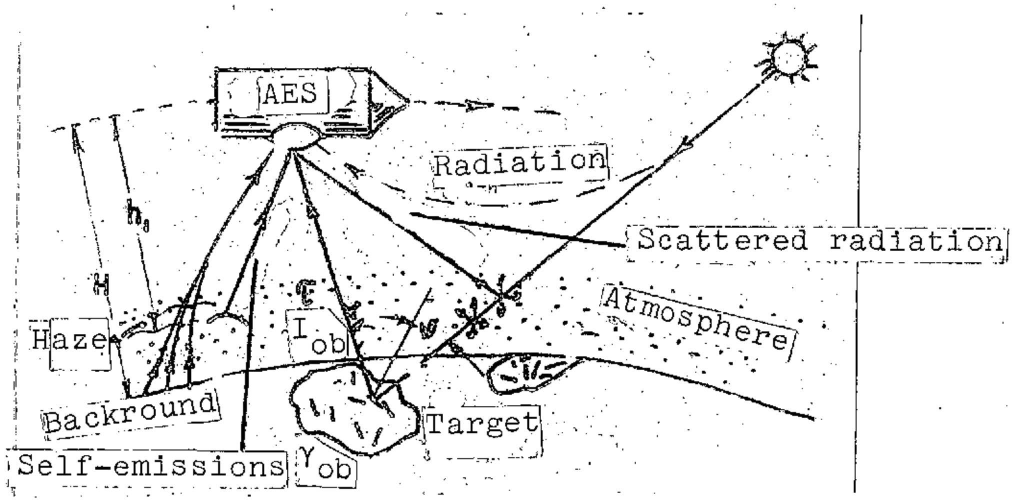


Figure 3

The eigen radiation of the Earth is determined in the same manner as that emitted by any body in thermodynamic equilibrium at a temperature T. The wavelength of maximum radiation corresponds to that given by Wien's Law: when T = 290° K, $\lambda_{max.rad.}$ = 10 microns. /10

Ninety-nine percent of the thermal radiation emitted by the Earth's surface is included in the range of wavelengths between 3 - 80 microns. Thus, even that portion of the Sun's energy which is absorbed and heats the Earth's surface is, in fact, detected again in the infrared portion of the spectrum.

Thus, the radiation spectrum from the Earth's surface has two main peaks: one at $\lambda \approx 0.5$ microns, produced by the reflected solar radiation, and the other at $\lambda \approx 10$ microns, due to its own thermal emission. The minimum between these two peaks lies in the region of 3.5 microns (see Figure 2). This is an integral dependence, and in this sense it may be called the Earth's background spectrum. At night, the short wave minimum of the spectrum fades away.

In addition to the thermal radiation from the Earth's surface and from the atmosphere, when the spectrum is a continuous smoothly varying curve with a maximum determined by Wien's Law, the atmosphere and the various processes on Earth produce radiations with sharply defined line spectra. This is very often called a characteristic spectrum.

The atmosphere produces narrow line spectra, generated by atomic and molecular processes and electrical discharges in the atmosphere. We already know that changes in the rotational and vibrational energy states of H_2O, O_2, and CO_2 molecules are significant sources of characteristic radiations from the atmosphere.

From the Earth's surface, characteristic emissions occur, for example, as a result of combustion processes: forest and prairie fires, fires, bog fires, etc.

Water vapor and carbon dioxide gas are the most frequent products of combustion processes. During combustion, an intense emission band occurs in the range of 4 - 5 microns (CO_2), as well as a less intense one around 2.7 microns (superposition of H_2O and CO_2). A line spectrum around 3.5 microns is produced when hydrogen chloride is formed during combustion. /12

Estimation of Atmospheric Effects

The atmosphere substantially affects the transmission of visible /13
and infrared radiations. As a result, radiation parameters detected by satellite instrumentation from objects on the Earth differ from those which occur in reality (without atmospheric effect). The estimation of this effect is difficult.

Satellite instrumentation responds to the radiant flux from ground objects P^{*}_{ob}. Since the view angle of the instrument and the area of the sensitive surface are usually known, it is possible to determine the brightness of the object I^{k}_{ob}, which presents the radiant flux at a unit solid angle and a unit area. When the magnitude of the incident flux P_n is known, then the reflectivity coefficient may be calculated from:

$$\rho = \frac{P^{*}_{ob}}{P_n} .$$

If it is assumed that there is no cloud cover, and that atmospheric scattering is primarily determined by haze (this is a real case when the surface is visible), then:

$$I^{*}_{ob} = I_{ob}\tau + I_h ,$$

where τ — atmospheric transmission coefficient over the object;

I_h — overall brightness of the haze, which over small ground objects is assumed to be equal to that over surrounding background;

I_{ob} — the unknown brightness of the object at the surface.

The brightness of ground objects I_{ob} depends on its own characteristics γ_{ob} (primarily surface characteristics), on the wavelength λ at which the measurement is made, and on the view angle ϕ (Figure 3).

The atmospheric transmission coefficient τ depends on the optical state of the atmosphere γ_{atm} (specifically, on the degree of optical transparency), on the wavelength λ, and the view angle ϕ. /14
The overall brightness of the haze I_h also depends on γ_h, λ, ϕ, and, in addition, on the height of the atmospheric distribution above the haze and the brightness of objects below the haze, that is, on the effects of multiple scattering.

If the indicated quantities are taken for a single band, corresponding to spectral values $I_{ob,\lambda}$, τ_λ, $I_{h,\lambda}$ (s subscripted by λ), then the equation for the remote sensing of the brightness can be written:

$$I^*_{ob} = \int_{\lambda_1}^{\lambda_2} I_{ob,\lambda}(\gamma_{ob},\varphi)\cdot\tau_\lambda(\gamma_{atm},\varphi)\,d\lambda + \int_H^0\int_{\lambda_1}^{\lambda_2} I_{g,\lambda}(h_1)\cdot\tau_\lambda(h_1)\,d\lambda\,dh_1.$$

The limits λ_1 and λ_2 are determined in practice by the detector's bandpass. When the radiation flux from a ground object is due to not only the reflected solar radiation, but also due to its own radiation, then the first integral will include the sum of two terms I_{ob} and $I_{ob.self}$. In practice, this takes place in the windows from 1 - 15 microns.

Theoretically, it is necessary to set up a spectral and spatial atmospheric model, and to take into account the scattering and the parameters which determine the reflective properties of the surface.

Experimentally, the method consists in determining the brightness of objects in the immediate vicinity as well as at a distance, when measurements are affected by the atmosphere. However, in addition, it is necessary to take into account the view angles, the time of measurements and, what is most difficult, to know the scatter in the parameters of similar surface types and the variation of atmospheric properties at different locations and at different times.

Principal Characteristics of Differences Between Remotely Sensed Ground Objects

Emitted or reflected radiation from ground formations, reaching the instrumentation of AES, can be categorized according to various agents. These agents affect the amplitude, frequency, phase, and polarization of electromagnetic waves. /15

Moreover, it is possible to make a selective spatial selection of the radiation coming from distinct elements of the observed ground objects. Naturally, all these alternatives may be utilized not only concurrently, but also repeatedly.

In accordance with this, the recognition of ground formations and their characteristics utilizes, most frequently, the differences found in:

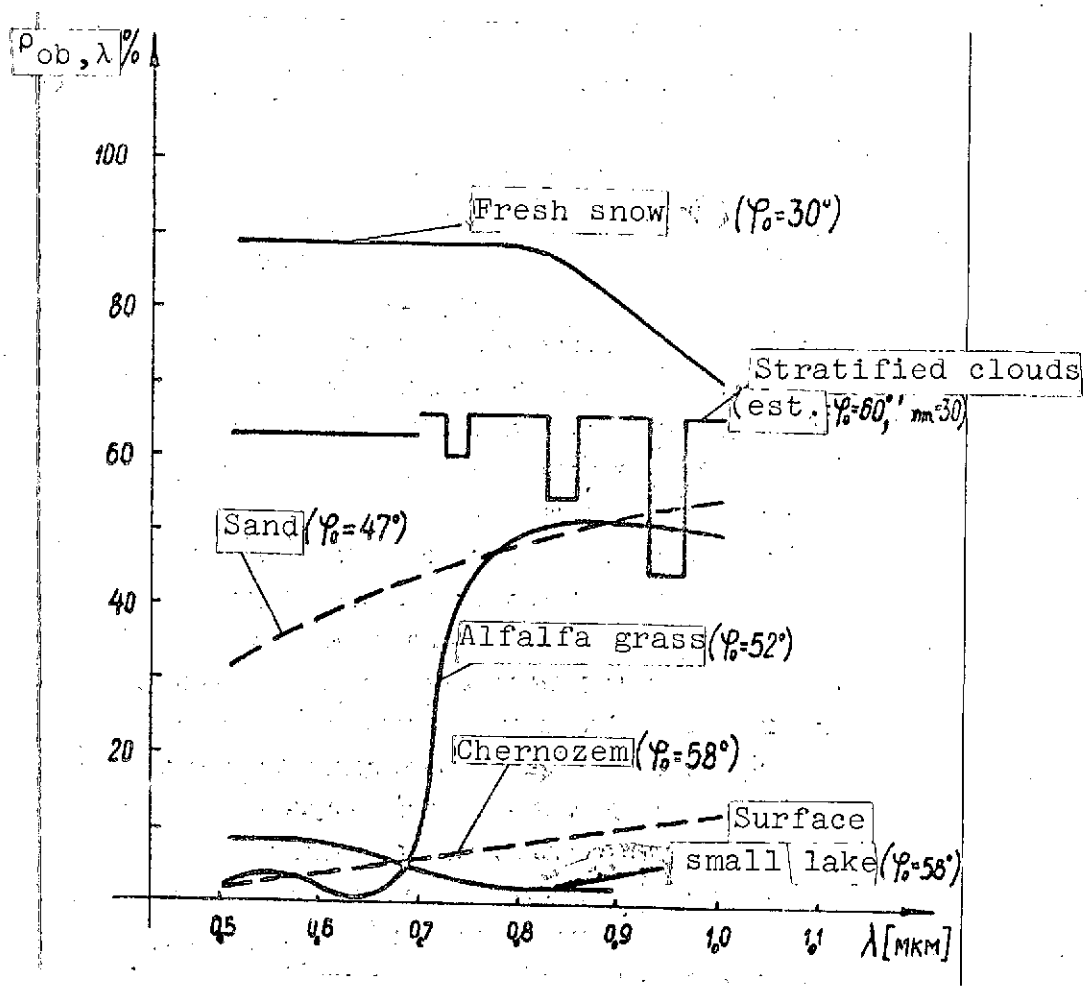
- the emitted (reflected) spectra of the objects,
- the form and texture of the images of the objects,
- the time dependence of the indicated and other parameters. Many repeated measurements (observations) are required, of course, to establish this dependence.

Thus, the recognition methods of ground formation from space are based on the determination of their spectral, geometric, and evolutionary characteristics.

In all cases, the result of remote sensing must be tied in with cartographic and temporal data. Numerous experiments and theoretical analyses indicate that spectral characteristics of radiations from various natural objects differ from one another to a greater or lesser degree. The term spectral characteristics implies the dependence of: the brightness I_{ob} (λ) and reflectivity ρ_{ob} (λ) on frequency of wavelength. The dependence of the effective temperature T_{eff} on the frequency is often used for emitted radiation, as well as other relationships. /16

Differences in spectral characteristics may be observed in various regions of the electromagnetic spectrum available for use by AES or other flying devices. Thus, the instrumentation for remote sensing has to be designed based on the most significant differences between natural features.

Figure 4 gives the dependence of $\rho_{ob,\lambda}$ on λ in the visible and near infrared regions of the spectrum for five types of the Earth's surface and for stratified cloud layers. It is evident from the figure that the nature of the spectral for all objects is very similar in the range from 0.5 to 0.65 microns. Between 0.6 and 0.9 microns, the nature of the spectra is dissimilar: $\rho_{alfalfa}$ rises



ϕ_0 — view angle

Figure 4

sharply and peaks in the near infrared, ρ_{water} decreases uniformly, $\rho_{chernozem}$ increases monotonically, while ρ_{clouds} has sharp, short dips. If man could see in the near infrared region, then grass would not seem green, but would be redder than red.

If the AES instrumentation could measure in detail, point by point, the indicated spectra, then the identification of all objects could be made from their differences. However, if the detector measures I_{ob} or ρ_{ob}, for example, only in two narrow spectral bands, then it apparently does make a difference just how these bands are chosen. For example, a relatively reliable identification can be made by comparing ratios for two bands of the spectra around 0.65 and 0.85 microns. The atmosphere has approximately the same effect, and the spectra of the objects differ widely in these spectral bands.

These ratios are indicated in the table.

Albedo ratio	Vegetation	Soil	Snow cover	Clouds and water surfaces
$\rho_{0.85}/\rho_{0.65}$	4 - 15	1.2 - 3	0.75 - 1.0	0.9 - 1.0

Of course, the variety in the condition of similar types of surfaces does not exclude deviations from the indicated values. Therefore, it becomes necessary to resort to measurements in other portions of the spectrum as well. The problem consists in determining the spectral characteristics of various natural formations under various conditions. /18

The recognition of objects by form, distribution, texture (sequencing or distribution of various elements), and other geometric signs is one of the most familiar methods of discriminating photographic or video images. The identification of objects according to such geometric characteristics is well accepted in the visible range of radiation.

Naturally, the above mentioned system was not only adopted but also developed for the remote indication of natural features from space. Images were obtained in the invisible portion of the electromagnetic spectrum by means of special transformations of measurement results. For example, images were obtained in the infrared and radio bands that could be studied visually. Furthermore, man's reliance on the visual extraction of information has led to the fact that now, in the first stage of development of the true bearing of a radio station (IPR) from space, most of the information users want it in image form. This fact alone should not be considered as an indisputable argument in favor of images. More appropriately, this indicates the weakness of quantitative methods in evaluating natureal resources and their condition. In the final analysis, a quantitative evaluation of the characteristics of natural resources is needed. The necessity of automatic data processing also requires that this data be presented in quantitative form.

Therefore, photographic, video, radio, and infrared representations must have metric qualities not only in the geometric (coordinates x, y, z), but also in the radiometric sense (brightness, reflectivity, etc.).

The possibility of carry out from satellites repeated measure- /19
ments of the characteristics of natural resources at different times (that is, determining their dependence on time t) allows one to trace the evolution of an object or phenomenon. In addition, once this dependence is established, the recognition of various objects can be made.

The time dependence may be established by:

— the changing conditions of observation (for example, changing position of the Sun);

— the daily and yearly temperature changes, which are primarily brought about by the changing position of the object relative to the Sun;

— the development of internal processes in the objects (the growth of plants, their diseases, flooding, etc.), which are frequently tied in with seasonal variations.

Figure 5 shows the seasonal dependence of the integral reflectivity (in the visible region) of the surface of a lake. During the summer months, ρ is small, and does not change significantly. During the winter months, ρ undergoes appreciable changes (approximately from 50 to 85%) due to snowfalls and thaws. Figure 6 gives the diurnal variations of the effective temperature of gravel, cement, and water.

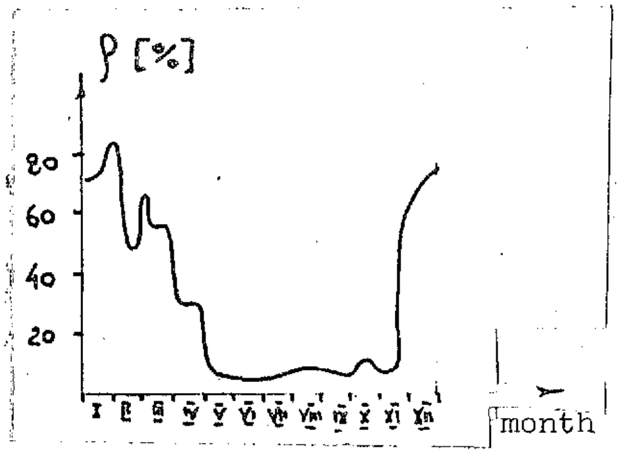


Figure 5

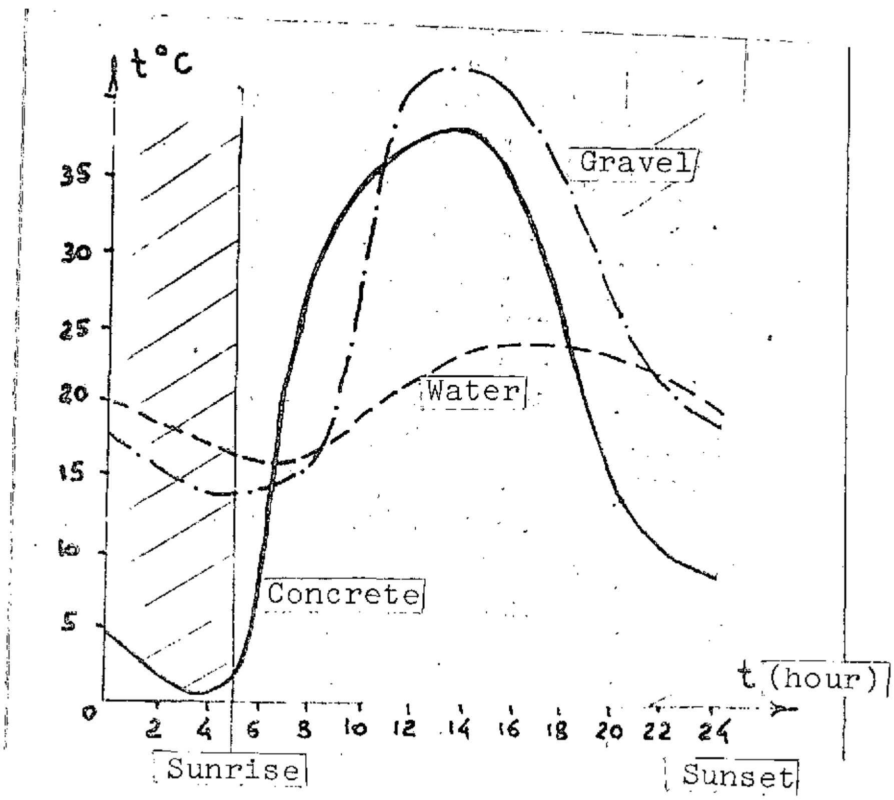


Figure 6

A material with large inertia is subjected to smaller variations in temperature. Therefore, the nature of the change with time of brightness, temperature, reflectivity can serve as a recognition criterion for ground objects.

The reliability in the discrimination of natural formations and in the determination of their characteristic increases with the concurrent utilization of two or three of the above mentioned criteria.

Recognition Criteria According to Spectral Characteristics

Let us examine the criteria for the discrimination of a few natural formations A, B, C, ..., I, J ... according to their spectral characteristics, and determine the amount of detail required for the analysis of the spectra of their radiations. That is, let us determine the number of frequency channels n required by the spectrometer. /21

Let us assume that the radiant flux has been measured and that ρ_I has been determined for each frequency channel, with a mean wavelength λ_K. That is, the values of $\rho_{A,K}$, $\rho_{B,K}$, ... $\rho_{I,K}$ are known for each ground object.

Let us assume that a particular region of the earth can have one of three types of surfaces: A — vegetation, B — chernozem, C — sand. The problem consists in recognizing with a minimum n any one of these surfaces. If we wish to make do with a two-channel spectrometer (n = 2), then we should examine Figure 9.

Figure 7 gives the spectral characteristics of objects A, B, and C (reproduced from Figure 4); Figure 8 represents a two-dimensional space. Values of $\rho_{I,1}$ (for $\lambda = \lambda_1$) and $\rho_{I,2}$ (for $\lambda = \lambda_2$) are plotted along the coordinate axes for all three objects. On the surface ($\rho_{I,1}$; $\rho_{I,2}$), three separate points A, B, and C can be seen, corresponding to three ground objects. If the first frequency

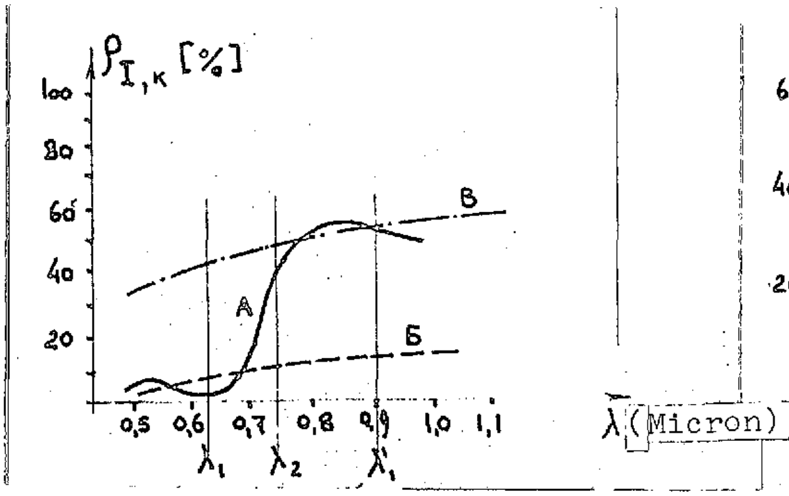


Figure 7

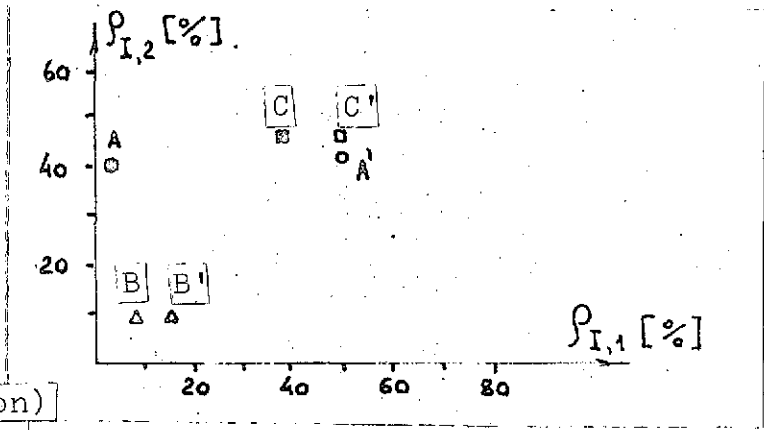


Figure 8

channel were to be chosen, for example, with $\lambda = \lambda_1'$, (see Figure 7), then of the three points A, B, and C, points A and C would almost coincide — that is, it would be difficult to discriminate between vegetation and sand.

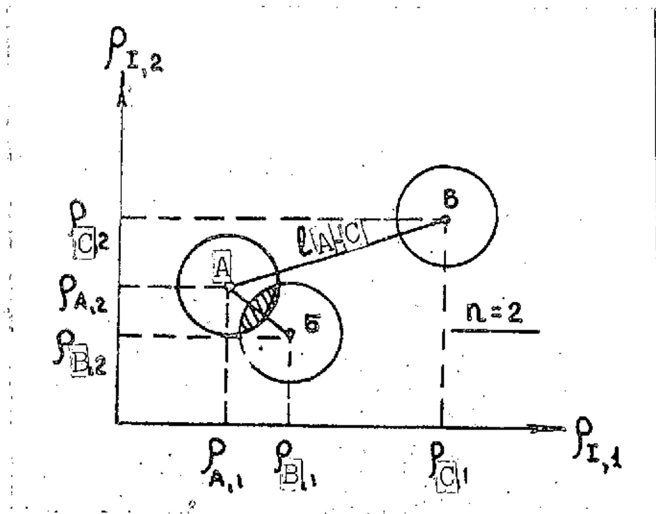


Figure 9

/23

The positions of points A, B, and C on the surface will change for different measurements depending upon the instrumentation error σ_{ins}, the variation in the properties of the same ground object σ_{ob}, and the changes in the conditions of observation (for example, due to the fact that the change in the atmosphere was not taken into account) σ_{atm}. Let us assume for simplicity, that the scatter in the values of ρ_I is the same for all channels λ_k, and is bounded by a circle of radius:

$$\sigma = \sqrt{\sigma_{ins}^2 + \sigma_{ob}^2 + \sigma_{atm}^2}$$

The geometric summation of these errors is allowable, since in the great majority of cases they are independent of each other. Figure 9 represents the case for particular values of λ_1 and λ_2 (this figure is not consistent with Figure 8), for which the regions of possible values for $\rho_{A,K}$ and $\rho_{B,K}$ overlap. Therefore, the distinction between objects A and B becomes difficult in the shaded portion.

Measurements of ρ_I may be made in one additional channel (n = 3) in order to make a reliable distinction between objects A and B. The examined geometrical representation becomes a three dimensional one, as is shown in Figure 10. In this case, as a result of the large difference between $\rho_{A,3}$ and $\rho_{B,3}$, the regions of uncertainty (scatter) bounded by spheres of radius σ no longer overlap. Therefore, all objects A, B, and C can be distinguished.

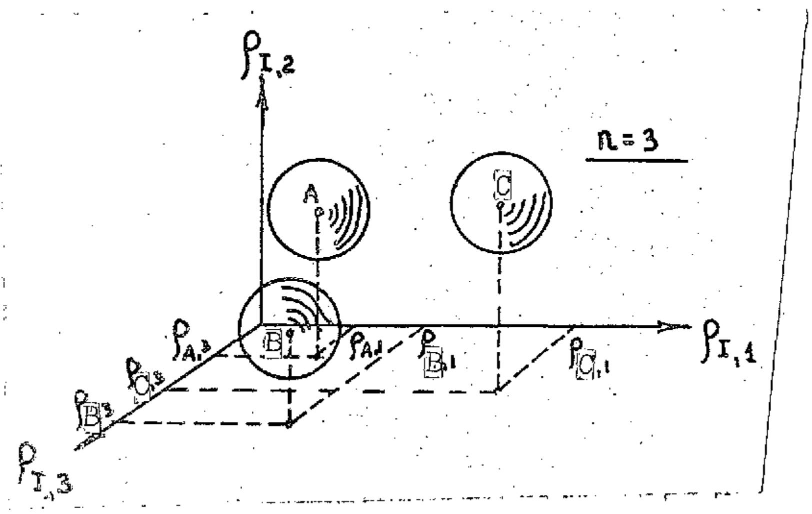


Figure 10

If, in this latter case, the objects could not have been distinguished, then it would have been necessary to introduce a fourth channel (n = 4), and to deal with a many-dimensional space. In the general case of a many-dimensional space, with orthogonal coordinates, the condition for the separation of any two objects I and J can be given by:

$$\sigma < \frac{1}{2} l_{I-J} = \frac{1}{2}\sqrt{\sum_{k=1}^{n} \left|\rho_{I,k} - \rho_{J,k}\right|^2}.$$

In the special, but most difficult case, when the recognition /25
of natural objects is made in spectral bands similar in form

(without marked differences), the condition can be written as:

$$\sigma < \frac{1}{2}\sqrt{n}\,\left|\rho_{I,K} - \rho_{J,K}\right|.$$

If, in addition, the spectrometer has channels with mean wavelengths of λ_K, then the number of channels required for the recognition of objects will be given by the expression:

$$n \geqslant \left(\frac{2\sigma}{|\rho_I - \rho_J|}\right)^2,$$

where $|\rho_I - \rho_J|$ is the absolute value of the difference between the reflectivity of the least dissimilar objects I and J.

The above mentioned considerations permit one to establish the conditions for the selection of λ_K of the frequency channels, as well as their number for the spectrometer:

1. The mean values λ_K must be within the transparent "windows" of the atmosphere, or in the regions where the atmospheric effects are approximately the same.

2. λ_K should be chosen in the regions of greatest special differences between natural formations. The best limiting case occurs when the spectra do not overlap.

3. The number of required measuring channels n for the analysis of overlapping spectra is determined, not by the number of natural formations to be recognized, but by the degree of dissimilarity under the actual conditions of remote sensing. The improved accuracy in the measurement or calculation of ρ_I (decrease in σ) permits a decrease in the number of required frequency channels (bands) of the instrumentation onboard the AES. A reduction of the total measurement error σ by a factor of two will reduce n by a factor of four.

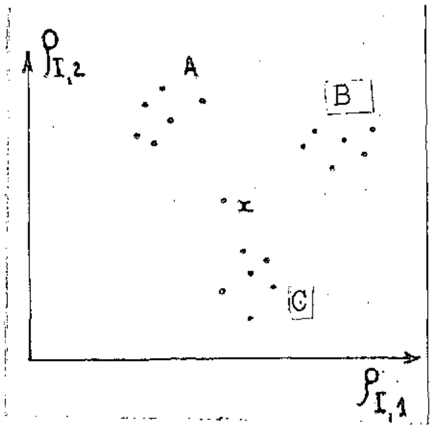


Figure 11

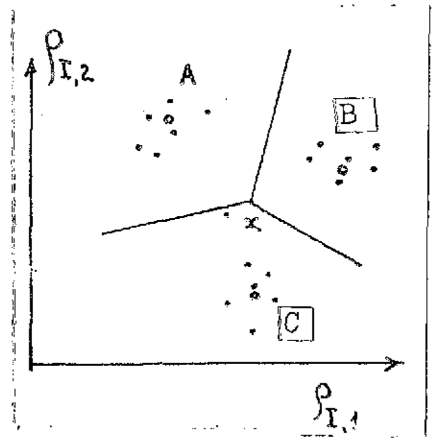


Figure 12

In actual measurements, values of ρ_I, plotted — for example, on the surface ($\rho_{I,1}$; $\rho_{I,2}$) — can be scattered over the entire area, and need not be limited by the region with radius σ. In relating these measurements to the shape of the objects A, B, C,...., I, J,... the question is raised as to how the boundaries between the areas of scatter should be set. There is also a question about results which do not fall within these areas, since it is not clear to what object these should then be attributed. /26

Let us assume again that in the region under study, three types of natural formations may exist — A, B, and C. The results of measurements are given in a two-dimensional space (Figure 11).

The clustered points, apparently, correspond to objects A, B, and C. However, it is difficult to say to which object the point "x" belongs. We can take advantage of the simplest criteria for the establishment of boundaries between "objects" — the criteria of mean points and equal distances.

In Figure 12, the mean points, defined by the coordinates $\frac{\Sigma\rho_{I,1}}{\text{no. of points}}$ and $\frac{\Sigma\rho_{I,2}}{\text{no. of points}}$ are represented by small circles. Straight lines are drawn between them, equidistant from each pair of "mean" points. These lines define the boundaries between objects. According to this criterion, the point "x" is attributed to object C.

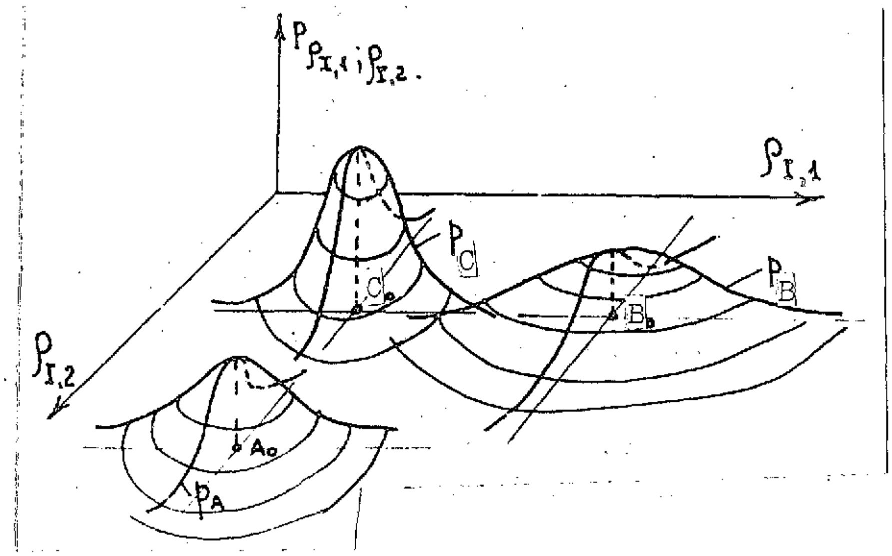


Figure 13

The discrimination of objects according to the criterion of mean points and equal distances is appropriate when, in the region of interest, the set of all possible objects is known. If an object is not taken into account in the classification, it will be classified erroneously as some other object. Frequently, it is more effective to exclude doubtful measurements from consideration, rather than including them in some predetermined class. In this case, a different set of criteria is necessary.

The examined solution to the problem of recognition of natural /28 formations (classes) is a probabilistic one by nature. The identification of objects from the results of measurements is made with a greater or lesser degree of confidence. Therefore, it becomes natural to exploit statistical models in the identification of measurements according to classes of objects. Experience confirms that statistical stability is one of the most dependable characteristics of many natural processes and phenomena. All this provides a very good argument in favor of statistical methods in the identification of natural formations and the determination of their characteristics.

An example of the representation of the results of spectral measurements having a Gaussian distribution of ρ_I is given in Figure 13. The required confidence level of recognition depends on specific problems.

Remote Sensing of Subsurface Resources

Sometimes surface characteristics reflect the properties of the interior. This relationship was long utilized in the exploration for mineral resources, underground water reservoirs, natural gas, etc. Nevertheless, among the IPR problems, many require for their solution a "look" into deep water or underlying rocks. /29

Along with the study of the surface vegetation or snow cover, it frequently becomes important to determine the properties of the underlying ground surface (soils) covered by vegetation or snow.

The depth of penetration of the electromagnetic wave in a semiconducting medium is determined by the losses, which depend on the frequency of oscillation $\omega = 2\pi f$, and on the complex dielectric constant:

$$\varepsilon' = \varepsilon - j\frac{\sigma}{\omega \varepsilon_0},$$

where ε — the permittivity of the medium;

σ — the electric conductivity in mhos;

ε_0 — the absolute dielectric constant in a vacuum, $\varepsilon_0 \approx 8.9 \cdot 10^{-12}$ F/m.

If it is assumed that the depth of penetration Z_0 is the distance over which the wave is attenuated by a factor of e, then,

$$Z_0 = \frac{c}{\omega}\sqrt{\frac{2}{|\varepsilon'| - \varepsilon}},$$

where c — velocity of light.

The magnitude Z_0 may be conveniently used to compare the absorbing properties of the medium in the infrared and radio wavelengths. Figure 14 shows the dependence of Z_0 on the moisture of sand and clay for λ = 3 cm and λ = 1 m.

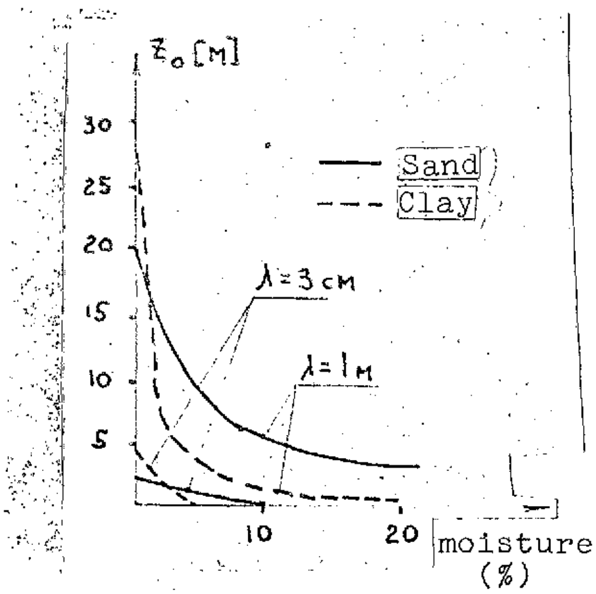


Figure 14

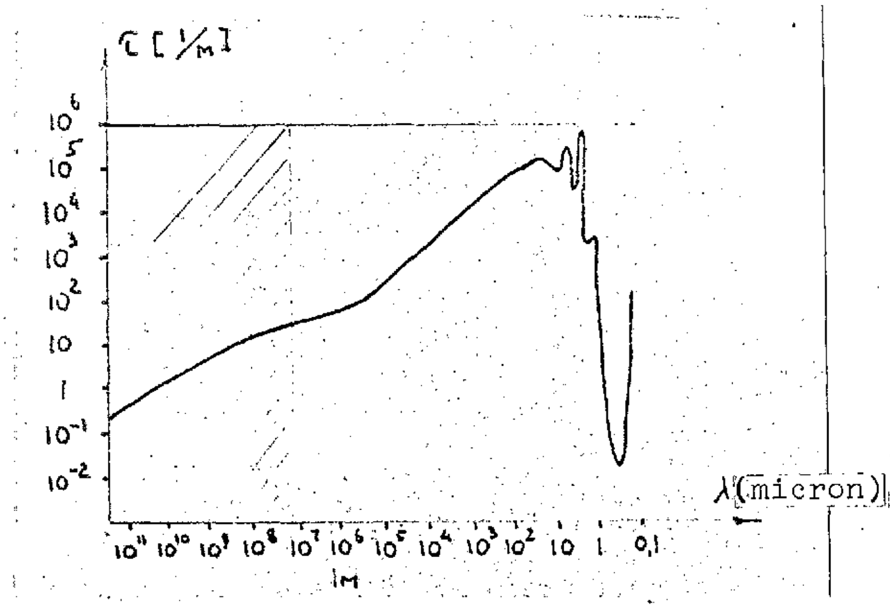


Figure 15

The magnitude of Z_0 changes between 2 - 30 meters. In order /31
to evaluate the penetration of electromagnetic oscillations into a transparent medium (sea, lake, and river water), Figure 15 gives the experimentally determined dependence of the coefficient of attenuation τ of sea water on frequency (wavelength). The "window" in the blue-green portion of the visible spectrum can be clearly seen. τ gradually decreases in the radio range with increasing λ. However, the frequency range below 15 - 30 MHz cannot be used for remote sensing from AES due to the ionospheric barrier.

Space Instrumentation

The parameters of AES motion, operational characteristics of all systems, the distribution of remote sensors, methods of time and spatial correlation of the results of interdependent measurements made from the satellite, and the sampling of data are determined by a compromise between user requirements and the technical capabilities of the data collecting systems. /32

From the economic point of view, the satellite system of the IPR must be designed with a minimum number of space instruments necessary for the solution of the investigated problem. In addition, the criteria in the selection of type, number, and orbit parameters of the AES can be:

1. The period of variation of the investigated processes, or the time constraints of the delivery of information to the users (operational, non-operational, and emergency data).

2. The territorial distribution (regional, global, latitudinal).

3. The desired conditions of observation (by day, by night, or at specified angles to the Sun).

4. The constraints on the collection and telemetry of data (number and location of ground stations, duration of radio contacts with the satellite).

5. The required composition and accuracy of the measurements.

Table 2 gives examples of the classification of problems according to the delivery rate of information to the users, and according to territorial distribution.

TABLE

Territorial scale Information delivery rate	Global, continental
Emergency — requires continuous observations and immediate delivery of information at the time of discovery of the phenomena	Discovery of storms, tsunami, intrusions from outer space (meteors, comets, etc.)
Operational — periodic observations and delivery of information (anywhere from several times a day to several times a year, seasonally)	Investigation of atmospheric and oceanic characteristics as a meteorological service function for the fishing industry, navigation; condition of icebergs, and currents
Non-operational — periodic observations with a frequency of once every 0.5 to 5 years with permissible delays in delivery of information	Mapping of the Earth, the study of its geoid, variations in the magnetic and gravitation fields; climatological changes; continental drift

Speaking of the observations themselves and of the delivery rates of information, we must keep in mind that natural phenomena themselves may be aperiodic. It is reasonable to assume that processes on Earth brough about by the diurnal rotation of the Earth and the yearly cycle of the Earth's rotation about the Sun are periodic. /34

Other phenomena (from the standpoint of remote sensing by satellites) will be considered periodic, that is, irregular, sudden phenomena, as well as very slow processes. It is understood that this is a tentative classification. Natural phenomena will be found that border on the perodic.

Three practical conclusions can be reached from the above classification. In the first place, photographic methods of remote sensing, associated with the necessity of returning photographic

National, large geographic regions	Local	Special "points"
Discovery of abrupt changes in the atmosphere and water basins	Discovery of forest fires and floods	Observation of known volcanos and dangerous faults
Control of air and water pollution; state of agricultural economy, land, forests, pastures, parasite infestations, diseases	Control of air and water quality; condition of agricultural economy and forest resources; ecology, condition of snow, ice covers, transportatn.	Observation of potentially dangerous glaciers
Geological problems, growth of cities, soil erosion, changes in the costline, geodesy and cartography		Observation of the evolution of unusual natural phenomena

materials to Earth (either by means of film capsules, return of the AES to Earth, or by the return of the crew) are useful, in general, for the solution of non-operational problems and the study of some long-term periodic operational processes. In the second place, problems of most branches of science are of an operational nature, and require for their solution methods which make possible the transmission of data collected on the AES back to Earth. Finally, the irregular nature of "emergency" phenomena and the possibility of their occurrence over any region of the Earth require uninterrupted and often global contact. In this case, the AES must carry out service (patrolling) functions, while the design of remote sensing instrumentation should follow the principle of "detected-transmitted".

Figure 16 shows the projection of the orbits of the AES and the Earth on a surface perpendicular to the plane of the orbit. The angle β is the angular inclination of the orbit; H is the height of the AES above the surface.

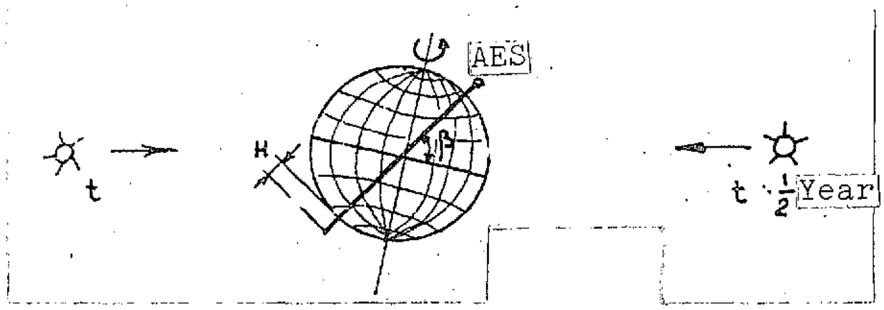


Figure 16

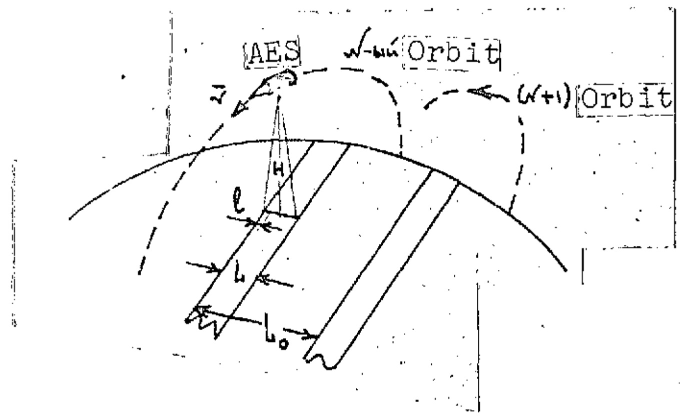


Figure 17

The direction of the Sun is also given at six month intervals. Figure 17 shows a larger-scale representation of two strips on the Earth's surface sequentially scanned by detectors on the AES along the line of flight. L is the width of the swath, defined by the view angle (field of view) of the sensor, while l is the linear resolution defined by the angular resolution of the sensor. L_0 is the distance between projections of successive orbits of the AES. It can be easily calculated from: /35

$$L_0 = v_{equ} \cdot T_{orbit} \cdot \cos \beta_{lat},$$

where v_{equ} — linear velocity of a point on the Earth's equator;

T_{orbit} — period of rotation of the satellite;

β_{lat} — latitude.

At the equator ($\beta_{lat} = 0$), and with $T_{orbit} = 1.5$ hours,

$$L_0 \approx 2500 \text{ km}.$$

These figures illustrate the effects of the orbit parameters on the results and conditions of measurements:

1. The inclination of the orbit determines the limiting latitude of view of the Earth, and the illumination of observed regions during the course of the year. Figure 18 shows lines of equal solar angle (from 20 to 80 degrees) at different times of the year at various inclinations of the AES orbit, that is, for different attainable latitudes of the Earth. It can be seen, for example, that at a latitude of 50°, even in summer, it is not possible to carry out remote sensing at solar angles of greater than 60 degrees.

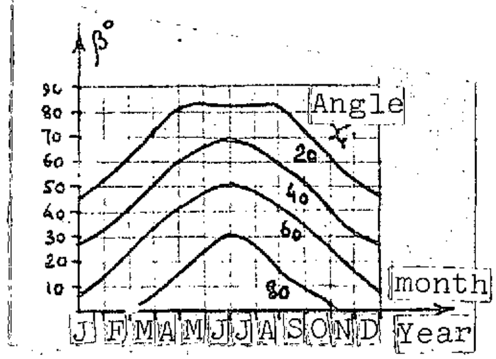


Figure 18

2. The shape of the orbit (eccentricity) affects the constancy of the scale of the surveys, the area and duration of the simultaneous visibility of different regions of the Earth. At apogee, the scale is minimized, while the area and duration of visibility is maximized.

3. The period of rotation (T_{orbit}) determines the distance between adjoining strips of view L_0 and, in part, the period of full coverage of the Earth.

T_{orbit} for a circular orbit depends on the height of the orbit. /37
For H = 200 - 1000 km, T_{orbit} = 85 - 100 minutes, thereafter increasing more noticeably. A geostationary orbit (T_{orbit} = 24 hours) is obtained for H $\approx$ 36,000 km.

4. With increasing height of the AES orbit, for given detector parameters, the swath width L increases with a proportionate deterioration in the linear resolution l. At the same time, the duration of visibility by ground stations increases, as well as the lifetime of the satellite.

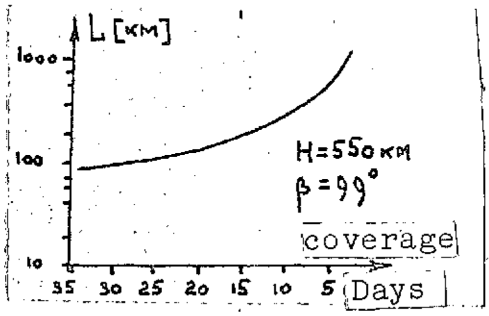


Figure 19

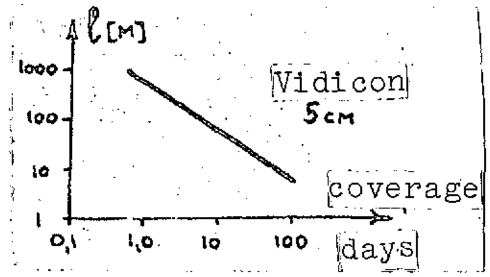


Figure 20

Thus, for a given l, the period of complete coverage of the Earth's surface (in the case of circumpolar orbits) is determined by the orbital parameters of the AES. Figure 19 gives the dependence of the period of complete coverage for H = 550 km, for the so-called solar-synchronous orbit.

It is apparent that even for wide swaths (L = 500 - 1000 km), the entire Earth's surface can be covered only in 4 - 7 days. Since the ratio of L/l for a given type of detector is a constant quantity, it is not possible to carry out a quick coverage of the Earth with high resolution.

Figure 20 illustrates the time dependence for complete coverage of the earth by means of a vidicon camera with a 5 cm screen for various resolution requirements l. When l = 1000 m, a global coverage may be made in less than 24 hours, while at a resolution of 10 m, more than 3 months will be required.

Results of observations of natural formations from reflected solar radiations, as we have established earlier, depend significantly on the solar position. Therefore, it is exceedingly tempting, especially in the experimental stage of the investigation of the Earth's natural resources, to create conditions such that the same ground objects can be observed (measured, imaged) repeatedly at one and the same local time of day, that is, decrease the uncertainty of observations due to different positions of the Sun. /38

It appears to be possible to select the AES orbit which meets this requirement. In the first place, the AES must complete an integral number of rotations during a 24-hour period in order to be located precisely over the same region of the Earth every day. That is, it is necessary that

$$T_{orbit} = \frac{24 \text{ hours}}{N}$$

where N is an integral number; for circular orbits at a height of 150 - 1000 km, N = 16, 15, 14, 13. These orbits are called periodic. In the second place, the plane of the AES orbit must be located at a constant angle to the Sun-Earth during the translation of the Earth around the Sun (see Figure 21, angle C_{orb}).

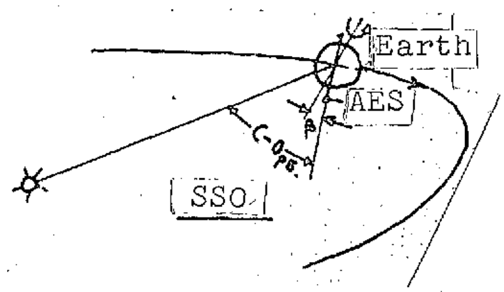


Figure 21

This must be attained by the inclination of the AES orbit by an angle β, which is greater than 90 degrees. Furthermore, the plane of the AES orbit will precess to the east. If the precessional velocity is on the order of one degree/day, it will compensate for the translation of the Earth around the Sun, which occurs at the rate of 360° per year. An orbit of this type is called a Sun-synchronous orbit (SSO or heliocentric). In practice, the velocity of rotation of the Earth around the Sun is not constant; the AES orbit undergoes perturbations as well. Therefore, it becomes necessary to correct the orbit of the satellite from time to time in order to retain a strict SSO.

Timely discoveries of emergencies are possible in nature only under continuous observation of the Earth from space. It is apparent that one AES is insufficient for continuous coverage on a global scale. The lower the orbit of the satellite, the smaller the area observed by satellite instrumentation. For example, approximately 30 satellites appropriately distributed in periodic orbits, with H = 800 km, will be required for uninterrupted coverage of the entire surface of the Earth.

The geosynchronous (stationary) orbits, whose plane corresponds with the equatorial plane, are of special interest. T_{orbit} = 24 hours, H = 35,860 km. Such an AES "sees" the Earth at an angle of 17.3°, and is almost stationary with respect to the Earth's surface. This assures the reception of data on Earth by a station with an antenna in a fixed direction. Instrumentation on a geosynchronous satellite can cover slightly less than half the Earth's surface. The equatorial diameter of the maximum spot is approximately 18,000 km, while its latitudinal coverage is to within ± 81°. The problem with AES geosynchronous satellites is due primarily to the difficulty in getting good resolution l from such high altitudes. In addition, periodic corrections in the orbits are needed to keep the satellites in these orbits. /39

Only 2% of the hemisphere, in the polar regions, will not be visible from a geosynchronous equatorial orbit. Three stationary AES, displaced every 120° along the orbit, would not only assure a constant global coverage of the Earth, but would also bring about the exchange of information between almost any points on Earth.

Thus, AES in polar orbits (including the SSO), in stationary orbits, and in low orbits (150 - 300 km) at various angular inclinations (for example, to obtain the maximum resolution in certain areas of the Earth) may be used in the investigation of natural resources.

Methods for Remote Sensing of Ground Formations

Remote sensing (telereception) of natural resources is carried out by detectors sensitive: to the reflected or emitted electromagnetic waves from Earth; to the variations in the magnetic and gravitational fields; and sometimes to the various types of particles, as well. /40

Taking the fact into account that the great majority of methods employed are based on the detection of electromagnetic radiation, the following classification may be proposed. This classification is not based on spectral bands, as is sometimes done, but indicates, rather, the principle of operation or the operational result of the instrument.

The fundamental methods, using sensing or measuring elements, are tentatively divided into four groups:

— recorders of images,
— detectors of natural radiations,
— active methods,
— detectors of penetrating radiations and fields.

Figure 22 represents the principal elements of remote sensing instrumentation. In some instruments, a number of the listed elements may be missing, with the exception of the collector of radiation and the sensitive elements. Let us now consider the classification, the general characteristics, and specifics of various types of remote sensing instrumentation.

Imagers constitute the most complex type of instrument. This category includes photocameras, including multiband; television and other devices with electric and magnetic electron beam scanning of a radiation sensitive target (screen). The screen may be, in practice, with low persistence as in television screens, or it may have a memory capability, as for example, in a vidicon; electromechanical /42 scanning devices, which successively concentrate radiations from various regions of the surface on one or more sensitive elements.

At best, photographic cameras record images directly on film in the wavelength range from 0.3 to 1.1 microns. Other instruments produce video signals. As a result, special devices — for example, electron-optical converters — are required in order to produce images. On the other hand, the video signal may be transmitted by radio from the satellite or, if necessary, recorded for any length of time on magnetic tape or by some other memory device. Vidicons

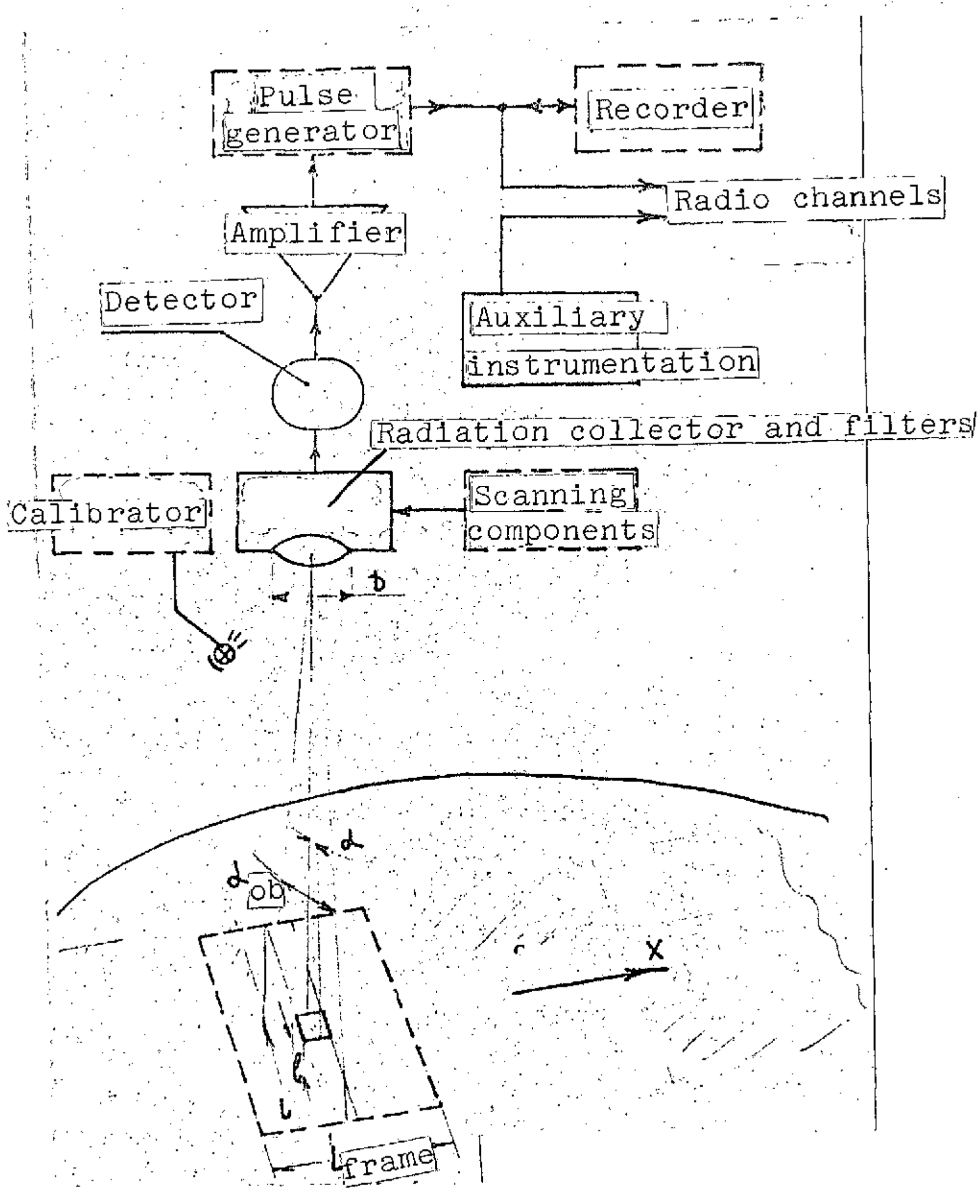


Figure 22

and scanning devices with photosensitive elements (photodiode, bolometers, etc.) can detect visible and infrared (up to 15 microns) radiation. Finally, UHF scanning radiometer makes possible radiothermal imaging.

Instruments of the first two types belong to the passive category. They react to the natural electromagnetic radiation, usuallly to the intensity (level). Active devices contain, in their design, an artificial source of radiation whose parameters may not only be known, but also controlled.

The following belong to the active category:

— radar-altimeter-profilemeter;

— radar-imager (for example, of the panoramic or side-looking types);

— laser altimeter-profilemeter;

— phase and Doppler shift detectors, and detectors of the polarized reflected signal;

— combination of radar and radiometric devices.

In contrast with the passive methods, the instrumentation in this group is not limited in its operation, as a rule, by time of day (solar) or by the weather. The added knowledge of the parameters of the incident radiation is compensated by an increase in the number of measurable parameters of the return signal (phase, polarization, frequency shift, shape, direction of propagation, and, of course, the intensity). /43

As discussed earlier, detectors operating in the radio range and blue-green visible range may be used as detectors of the penetrating (through the surface) signal.

Much is expected from magnetometers, gravitometers, and active methods in the radio range in the study of subsurface ores. The potential of these methods, operating from AES orbits, has not been fully realized, in comparison with the other groups. The investigation of the natural radioactivity of formations is in very much the same stage of development.

The abovementioned categories of methods of remote sensing provide information regarding parameters of radiation or fields. By themselves, these are insufficient. Therefore, service functions form an inherent part of the means of detection. These are required to provide spatial and time correlation for all measurements and surveys, calibration conditions for all satellite instrumentation and preliminary data reduction, control over the operation of the instrumentation, etc.

These include:

— position indicators (horizontal, vertical, etc.),
— star and topographic photographic cameras,
— time-programmed devices,
— sources of control signals, etc.

Let us examine in greater detail the more informative methods of remote sensing.

1. Photographic cameras

The wealth of long-term experience obtained from the study of ground objects from the results of aerial photosurveys naturally led to the immediate application of photographic cameras in recoverable devices from space. /45

One of the possible functional schematics for photographic cameras for IPR use is given in Figure 23, which shows a five band instrument. The objective lenses collect the radiation. Each of these contains a filter, characterized by a mean transmission wavelength coinciding with the maximum sensitivity of the film.

The optical axes of all the objectives are strictly parallel, and are "directed" at one and the same region of the Earth. The shutter control is exercised simultaneously by the synchronizer, which also provides for the advancement of the film. Markers or time marks, produced by transforming the electrical signal into a light signal, are recorded on the edge of the film. Calibration by means of a light source of known intensity (light diodes, lamps, Sun), is provided in the best cameras. The geometric calibration is

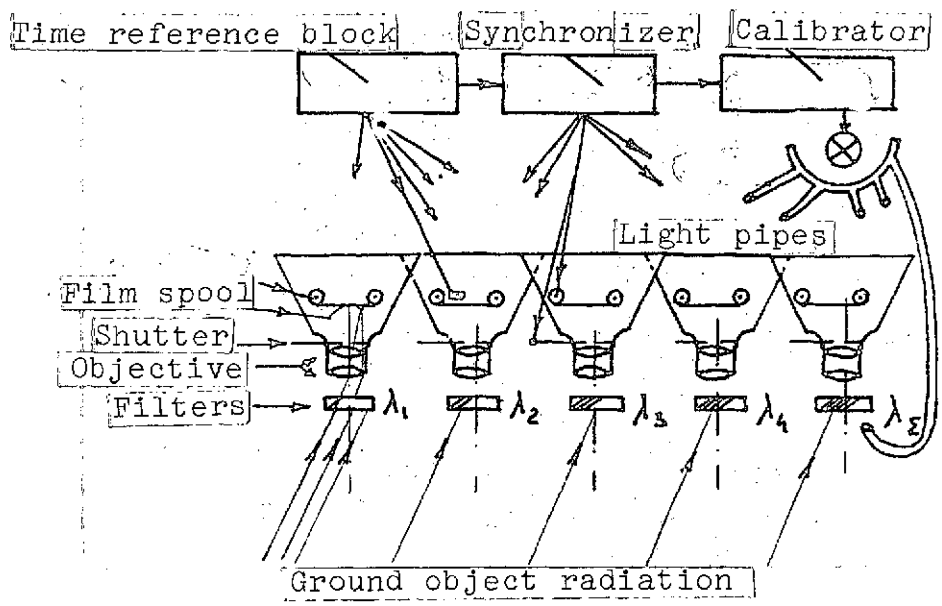


Figure 23

achieved by plotting on a transparent window (for example, cross hairs), divisions with rigidly specified dimensions (to $\pm$ 0.005 mm). The fixed location of the film in the focal plane for the entire frame is provided by means of special vacuum or mechanical retainers.

The view angle of the photographic camera α_{ob} is determined by the focal distance f and the format of the frame B. The short focal length objective ($f \geq 25$ mm), as well as the long focal length, telescopic, objective ($f \gtrsim 1000$ mm), with film size B = 35 - 300 mm, may be used, depending upon the purpose. Wide angle lenses of the type "Hasselbad", for example, have B = 70 mm, f = 80 mm, α_{ob} = 2 arctg; B/2f = 50°.

Wide angle lenses have α_{ob} = 90 - 120°. The angular resolution capability for a given B/f changes considerably, depending upon the properties of the film. In the visible range (0.4 - 0.7 microns) films have a resolution capability of b = 100 - 1000 1 /mm; color film and infrared film, in this respect, are significantly inferior: b = 25 - 250 1 /mm. /46

Attempts to use high resolution film may be fruitless if low resolution objective is used. The brightness and contrast of photographed objects is of primary importance in the selection of film. It would seem that the secondary parameters of the film, such as the thickness of base which limits the film reserve in the camera would also be of importance. The temperature stability of the sensitivity of the emulsion layer may require cryostats or thermostats, etc.

For the abovementioned camera with a film b = 100 lp/mm, the angular resolution is equal to:

$$\alpha = \frac{\alpha_{ob}}{B \cdot b} = \frac{50}{70 \cdot 100} = 30''.$$

This means that at an altitude of H = 500 km,

$$L = 40 \text{ km}, \; l \approx 70 \text{ km}.$$

In addition, the exposure time must not exceed:

$$\tau \leq \frac{l}{v_{AES}} \approx 0.01 \text{ sec}.$$

The sensitivity and dynamic range of the photographic camera are the most difficultly stabilized parameters. These depend on the properties of the film and on the characteristics of the objective and filters. They have a strong frequency dependence.

To facilitate the photometric interpretation of photographs, a sensitometric scale is "included" in each frame which allows direct comparison to determine the flux of radiation incident on each region of the film. The linear region of dependence of the film density (gray scale) on the intensity (or radiation flux) is approximately 25 - 40.

Order of magnitude of film sensitivity is approximately 10^{-6} $W/cm^2 \cdot$ micron. The spectral resolution of multiband cameras, determined by filters, is approximately 0.05 microns.

II. Television

The very first meteorological satellites were equipped with TV cameras, which imaged clouds and major features on the Earth's surface. Due to the fact that the result of TV observations is in the form of an electrical signal, it can be transmitted by radio to ground stations either immediately or subsequent to recording. /49

Additional requirements were imposed on TV and photographic cameras for the study of resources. These included requirements on the metric properties (geometric and photometric), on the spectral resolution, and on the motion parameters of the AES.

The objective, just as in the photographic camera, is the collector of radiation incident from the Earth. The objective concentrates the radiation on the light sensitive target of the super-orthicon or vidicon. An electron beam is scanned across the pick-up tube by means of deflecting systems. The current in the outer collector ring varies with the changing illumination of various elements of the target. On loading the tube, the voltage output is in the form of a video signal, and is generated when the tube is illuminated. The amplitude is dependent on the illumination, and its duration and shape — on the method and speed of scanning by the electron beam.

The vidicon tube is a storing and integrating device. It can be sensitive to longer wavelengths of radiation up to 10 - 15 microns. The spectral sensitivity of the orthicon, on the other hand, is limited to :

$$\lambda = 0.8 - 1.1 \text{ microns},$$

due to the nature of the photoemitting process.

Figure 24 gives a functional schematic of a TV system designed to take advantage of the good features of both the vidicon and the orthicon. This design utilizes a photoconductive target and an electron multiplier of the return (reflected) beam.

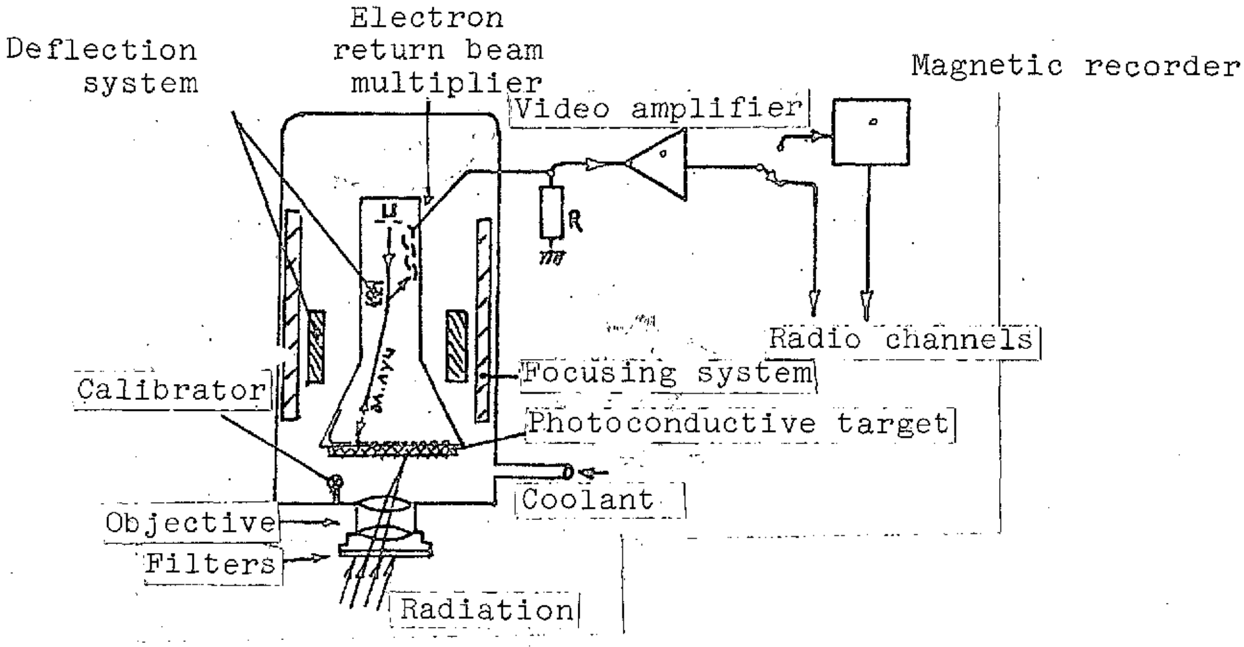


Figure 24.

The view angle α_{ob} of the TV is determined, as in the photographic cameras, by the ratio of B/f, where B is the dimension of the light sensitive area of the screen; usually, B = 20 - 50 mm for vidicons. The resolution, in contrast with the photographic cameras, does not only depend on the light sensitivity of the material and objective, but also on the construction of the electron tube (in particular, on the size of the beam cross section), on the parameters of the video amplifier, and of other components. /50

Since the information delivered by a TV system is extracted from the parameters of the video signal, then the resolving capability must be also determined by the parameters of this signal. In modern TV systems, the resolution (neglecting limitations of the video amplifier) is:

b = 20 - 200 cycles of the video signal/mm of screen.

This implies that the angular resolution of the TV system is:

$$\alpha = \frac{\alpha_{ob}}{1{,}000 - 10{,}000}.$$

The sensitivity of the TV systems is relatively high, and is approximately 10^{-7} W/cm^2 for a superorthicon in the middle portion of the visible spectrum, with $b \approx 100$. This corresponds to an illumination of 0.2 - 0.5 lux incident on the photocathode. The application of the so-called electron-optical converters raises the sensitivity by several orders of magnitude.

The persistence τ of TV systems may be limited by a number of factors. If τ is the exposure time, then in order to increase the sensitivity of the vidicon, it is desirable to increase it; however, it must remain less than:

$$\tau = \frac{l}{v_{AES}}$$

The next frame can be exposed (with a 10% overlap) after a time:

$$T = \frac{L}{1.1\ v_{AES}} = \frac{\alpha_{ob} \cdot H}{1.1\ v_{AES}}$$

During the interval between two exposures $(T - \tau)$, the video signal may be formed relatively slowly by high density electron beam scanning of the target. The target of the vidicon retains the charge during several tens of seconds. Assuming a square target, with side B, then the beam must cover: /51

$$(B \cdot b)^2 \text{ elements,}$$

in a time $(T - \tau - T_{ret})$, where T_{ret} is the time of return beam. For example, if $B \cdot b = 2500$; $\alpha_{ob} = 0.5$ rad; $H = 500$ km; $T_{ret} = 0.15\ T$, then the scanning speed must be equal to:

$$\frac{(B \cdot b)^2}{T - \tau - T_{ret}} \approx 250 \cdot 10^3 \text{ elements/sec.}$$

This corresponds to a spectral bandwidth of the video signal:

$$\Delta f \approx 125 \text{ MHz.}$$

For a superorthicon camera (without memory), the persistence is determined by the maximum attainable scanning speed of the frame. Thus, during a continuous transmission of all the image elements, the spectral bandwidth should be:

$$\Delta f \approx \frac{(B \cdot b)^2}{2\tau} \approx 250 \text{ MHz}$$

Present day radio links between AES-Earth do not have such bandwidths available. Modern magnetic recorders are capable of recording signals with a bandwidth not wider than 10 to 20 MHz. For these reasons, it is not feasible to undertake real time transmission, but instead use single frame television, transmitting 5 to 10 frames per second.

The light sensitive screen must have a certain amount of persistence; for example, the addition of phosphor makes it possible to achieve a persistence of more than 0.5 seconds in duration. In this case, the scanning speed may be reduced by a factor of a hundred, and the bandwidth of the video signal will become correspondingly narrower (0.5 to 3 MHz). /52

III. Scanning radiometers

Photographic and video cameras record simultaneously all elements of the surface region that "fits" into a frame of size (B x B). The electron beam scans sequentially each sensitive element of the target forming a video signal. /53

Scanning devices (as opposed to framing ones) contain one or more sensitive elements (detectors). Therefore, to obtain an image of the region of interest, it is necessary to direct sequentially the radiation from each element of this region towards the detector. This operation is performed by a scanning radiation detector. Figure 25 gives the schematic diagram of a scanning optical radiometer.

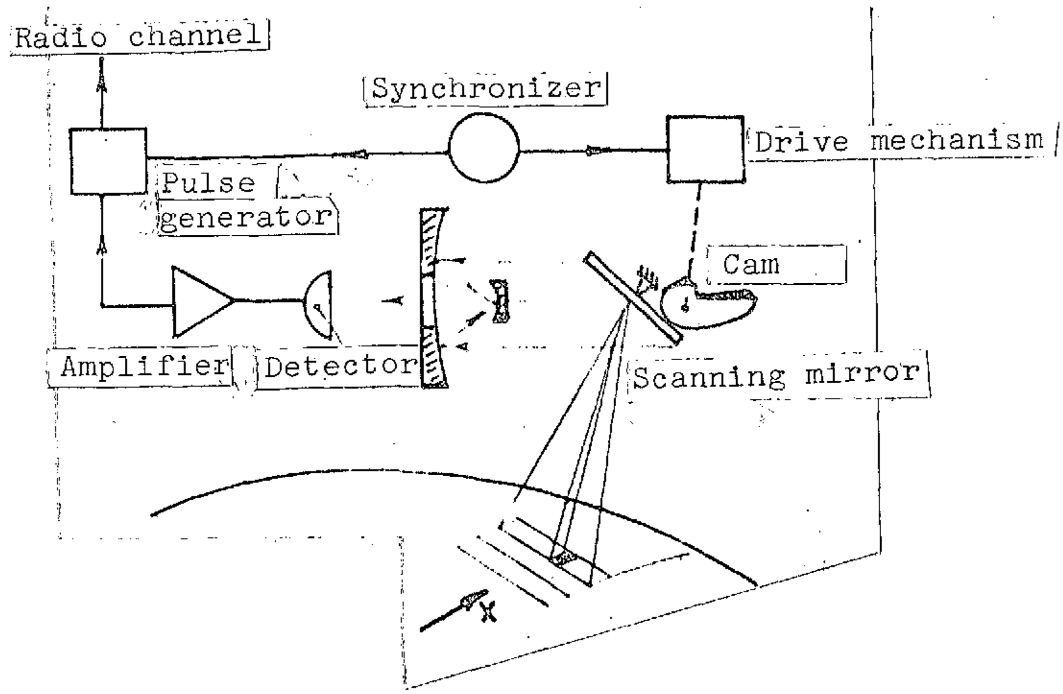


Figure 25

Radiation from the surface element is incident on an oscillating mirror, reflected from it, and directed toward an optical system which focuses it on the detector. The optical system and the detector are stationary. Therefore, according to the laws of geometric optics (equality between the angles of incidence and reflection), the scanning mirror will direct towards the detector radiation from various elements of the surface. The instrumentation is placed in the AES so as to perform the scan perpendicular to the line of flight.

In the radio range, the scanning radiometer includes either a mechanically rotating antenna (reflector or transmitter), or an electronically controlled antenna. In the latter case, the direction (maximum of the radiation pattern) is determined by the phase and amplitude relationships of the various antenna elements, forming the so-called antenna array.

Airborne optical scanning radiometers in some systems sometimes include both measuring and recording devices, so that the image of the surface is recorded immediately on film.

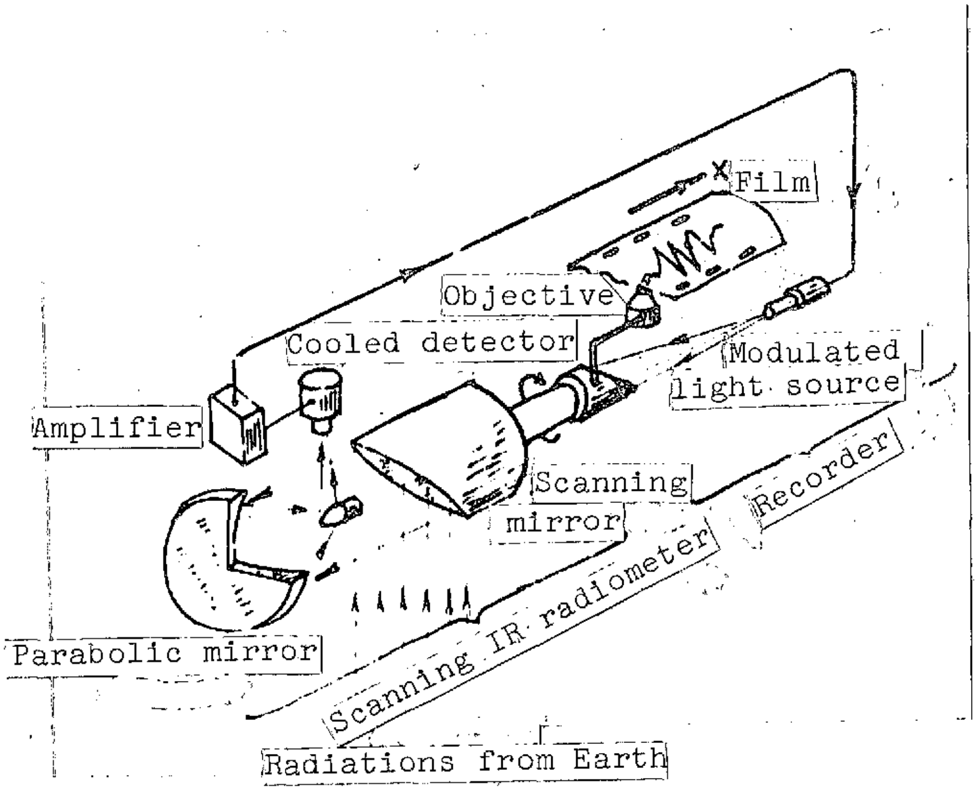


Figure 26

An example of such a combined device is given in Figure 26. /54
This device was used by American investigators to obtain images in the infrared range, where photographic cameras cannot be used. Here, the scanning mirror of the radiometer, which is in effect an inclined end-plane of a rotating cylinder, is located on the same axis as the mirror of the electron-optical recorder. As a result, scanning synchronizer devices are unnecessary. The detector is cooled to increase the sensitivity in the near infrared. The signal from the detector is amplified and modulates the intensity of the light source. The modulated light beam is reflected from the scanning mirror of the recorder, and is directed to a film by means of a rotating objective. The film is advanced at a rate proportional to the flight velocity of the airplane. Thus, this device performs measurements in the infrared region, converts them to the visible range, and delivers the results in photographic form.

The scanning of surfaces and the generation of the signal are performed sequentially element by element. Therefore, in contrast with various single frame TV devices, it is not possible to increase the signal generation time in comparison with the time of the radiation flux measurement. The diagrams give only single channel devices. In order to obtain multispectral images, the scanning device should contain N channels. Since the most cumbersome and complicated part of the device is the optical-mechanical system, containing the scanning mirror, objective, and reflector, there is a tendency in the design of a multiband scanning radiometer to include a common optical-mechanical system for all bands. Furthermore, the separation of the total flux into N channels requires the use of beam splitting devices and (or) filters.

A beam splitting device produces a spatial separation of the total flux into beams of radiation with mean wavelengths λ_1, λ_2, ... λ_n, and directs each beam towards it own detector. /56

The angular resolution of the scanning radiometer, as is the case in other types of remote sensing devices, is determined by the ratio λ/D (where D is the diameter of the entry pupil or aperture), and by the degree of the focusing of the incident radiation. The radiation detector, corresponding actually to one of the elements of the target of the TV pickup tube or to the sensitive layer of the film, does not in practice affect α.

Optical radiometers with D = 10 - 20 cm have $\alpha \approx$ 0.1 to 0.2 m radians, or 0.4 - 1.' In the infrared region (10 - 15 microns), α is worse by a factor of 5 - 10.

If the view angle in photographic and TV cameras α_{ob} depends on the size of the film or target, then, in this case, the detector is almost a point (the area is fractions of a square millimeter), and the value of α_{ob} is determined by the effective scanning angle. In turn, the scanning angle is limited by the permissible geometric distortion and by the construction of the detector and scanning element. α_{ob} = 5 - 10° for the more sensitive instruments, and α_{ob} = 15 - 60° for survey type instruments.

Semiconducting photodiodes and photoelectron multipliers are most commonly used as radiation detectors in scanning radiometers. Their sensitivity is determined primarily by noise.

The scanning time constant of the radiometer is determined by the time constant of the detector itself and by the integration time (transparent strip of the instrument). It must not exceed (l/v_{AES} · α/α_{ob}), i.e., the value of τ of the scanning radiometer must be α_{ob}/α times smaller than that of the framing devices.

To decrease the scanning frequency and to increase the permissible value of τ, one can resort to the use of several detectors for each spectral band. The detectors are placed in a line parallel to the direction of flight. As a result, the scanning mirror simultaneously directs radiation to the detectors from different elements of the surface, located along the line of flight. In this manner, multilinear scanning may be carried out in practice. At the same time, the scanning frequency may be decreased by a factor equal to the number of detectors in each band. Naturally, this is accomplished not only at the expense of increasing the number of detectors, but also by increasing the complexity of all succeeding cascades. /57

The main advantage of the scanning radiometers over the video and photographic cameras is the wide spectral response of the former. The video signal corresponding to the image of the scanned surface can be obtained practically over the entire useful range of the electromagnetic spectrum. In the optical range, this is limited to 0.3 - 15 microns.

The spectral resolution is determined by the filters, and may be equal to 0.05 - 5 microns. In the infrared region, it is imperative to choose the corresponding detector, as well as the collecting optics, to be transparent to the infrared wavelengths. Common glass is not transparent to λ greater than 2.5 microns. Sapphire is transparent in the region from 0.3 - 5.5 microns, silicon — in the region from 1 - 15 microns, cadmium-tellurium — from 0.8 - 30 microns.

IV. Active radio methods

The intensity of the solar radiation in the radio range is negligible in comparison with the intensity in the optical range. As a result, if the Earth's diurnal radio emissions differ from those emitted at night, it is only because of the difference in thermal heating. /58

The intensity of radio emissions from Earth formations is only from 10^{-12} to 10^{-14} W/cm^2. However, this is not below the sensitivity threshold of radiometers, since it is possible to use, in the radio frequency range, relatively low noise preamplifiers (parametric, traveling wave tubes, transistorized). Due to the small D/λ ratio, passive radiometers in the radio range have low resolution capabilities.

It is important to note that, although the range of useful frequencies (wavelengths) in the optical range is approximately 10,000 times larger than in the radio region, the frequency span turns out to be greater by hundreds in the radio range:

$$\left(\frac{\lambda_{max}}{\lambda_{min}}\right)_{opt} \simeq 3\,; \quad \left(\frac{\lambda_{max}}{\lambda_{min}}\right)_{radio} \geq 1000.$$

This implies that in the radio range one may look for spectral characteristics of Earth formations in a significantly larger frequency range. In addition, in the radio range, it is possible to measure the roughness of the surface and the dielectric properties of ground formation.

The possibility of generating radio waves with spectral intensities not less than those produced by the Sun, and with well-known and controlled parameters (frequency, polarization, duration, intensity, directionality), places active devices in a class by themselves. Their primary advantages are the following:

— independence from weather conditions and time of day; /59

— the possibility of obtaining images and maps of distributions of physical parameters of the surface and subsurface ground formations;

— full or partial independence of the scale from altitude;

— the possibility of obtaining contrast images of optically low contrast objects;

— the possibility of obtaining significantly improved resolution over that given by UHF radiometers.

Let us consider the schematic diagram of an active image recorder, built according to the principles of a side looking radar. Figure 27 shows a system with an antenna, with dimensions b > a. This means that the view angle along the line of flight (angle β) is less than α_{ob}. Furthermore, the antenna is directed sideways from the line of flight. In order to obtain a radio image, one must be able to distinguish the return from various elements of the strip L. In the figure, these elements are arbitrarily divided into bands of width l.

The transmitter emits a series of signals with duration τ_{sig}, repetition rate T_{rep}. The return, reflected from element 1, will have a delay of:

$$\Delta T_1 = \frac{2\ell_{min}}{c}$$

The returns from elements 2, 3, etc., will have delays $\Delta T_2 > \Delta T_1$, $\Delta T_3 > \Delta T_2$, and so on. Finally,

$$\Delta T_n = \frac{2\ell_{max}}{c}$$

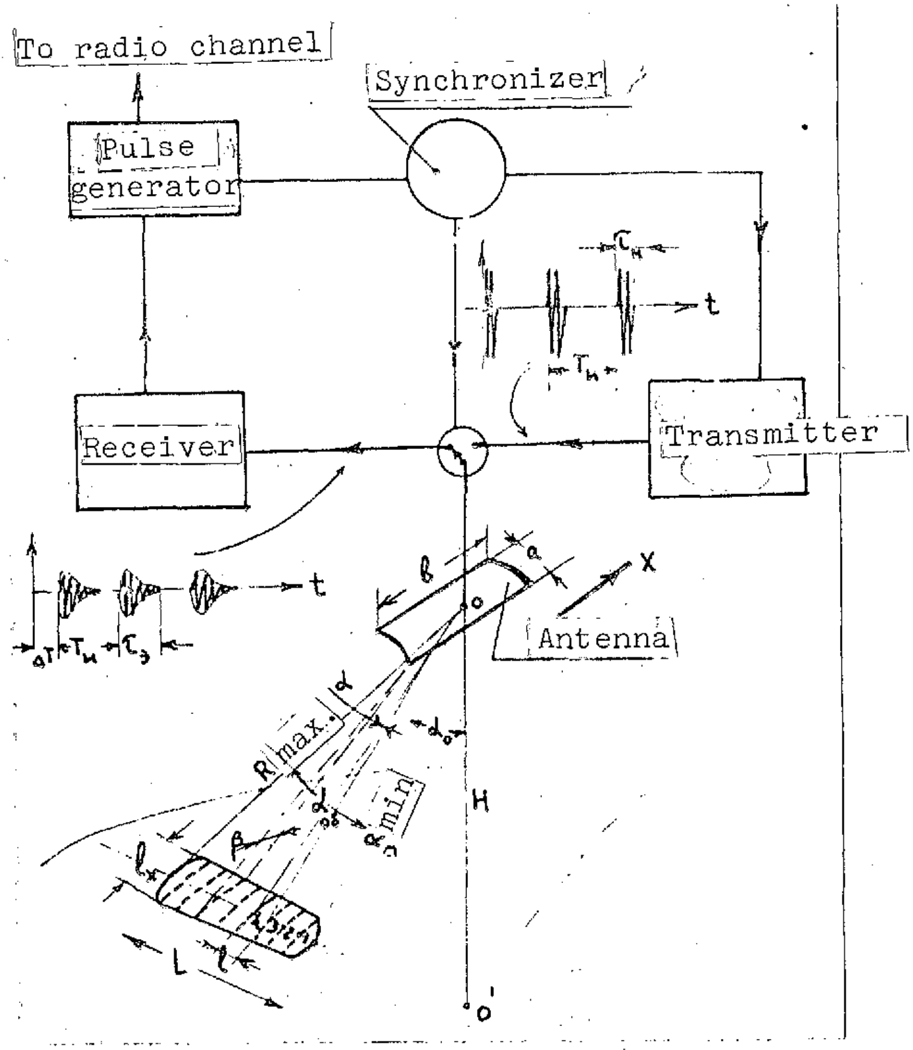


Figure 27

Thus, the system performs an element by element coverage of the area under study on the Earth's surface by selectively choosing an appropriate return signal. There is no selection possible along the direction of flight. The dimension of the element is determined by the angle β and distance R.

In order to keep track of the intervals ΔT, and to make possible the reception of very weak returns, the system includes a synchronizer which connects the receiver to the antenna during the intervals between probing pulses of the transmitter. The synchronizer also generates synchronizing pulses for the formation of the composite /61 video signal, so that during recording, the beginning of each cycle can be determined. The limiting resolution l is determined by the ability to differentiate between ΔT_n and ΔT_{n-1}, that is, the duration of the pulse which is approximately equal to:

$$l \approx \frac{c\tau_{imp}}{2}$$

A significant increase in the size of the antenna even in one direction (size "b") also presents a problem. The shape of the element of resolution on the surface for a side looking radar is a strip ($l \times l_x$) extended along the line of flight, so that $l_x \gg l$.

The principle of the synthetic aperture of the antenna may be used to improve the resolution of l_x without increasing the physical dimensions of the antenna.

According to antenna theory, it is well known that the directivity of a multi-element antenna array narrows with the increasing number of antenna elements. This effect is achieved only provided that the signals received by the antenna elements will be added coherently. In other words, the path length (as well as time delay) between the irradiated object on the surface and the summing network must be the same for all antennas. Consequently, the difference in path length from a point on the surface to the antenna must be compensated, for example, by the difference in cable length (wave guides) from the antenna to the integrator (Figure 28).

Let us assume now that there is only one antenna with dimension D which moves along together with the AES or airplane, as shown in Figure 29, taking up positions 1, 2, 3, 4, 5, etc. Then, in order to add the signals coherently, it is necessary to recall the phases of the signals received at different positions of the antenna and, subsequently, after a flight path of $n \cdot D$ meters to carry out the summation. A similar process has to be followed for all points located at intervals equal to the desired resolution l_x. /63

Thus, if such a synthetic aperture has the length L_x, the the resolution l_x will be equal to:

$$\ell_x = \frac{\lambda}{L_x} \cdot R,$$ and since $$\frac{\lambda}{D} = \frac{L_x}{R},$$ then $$\ell_x = D.$$

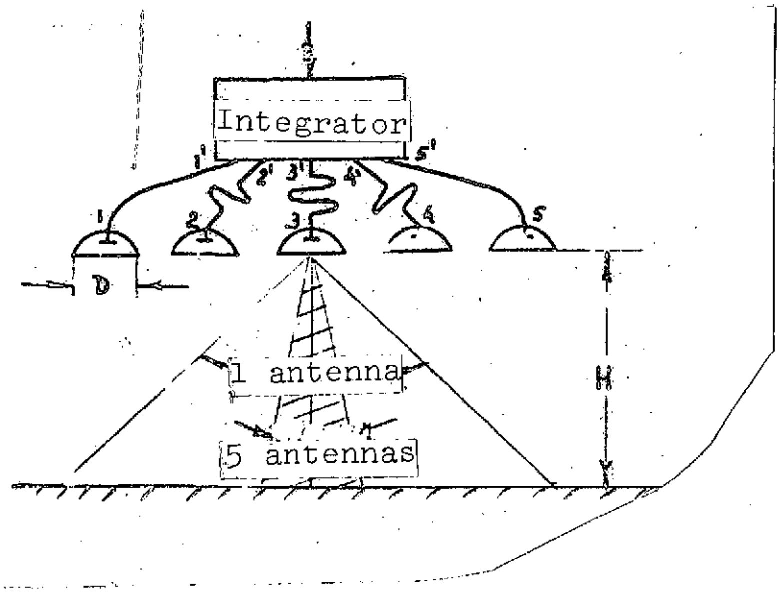


Figure 28

That is, the linear resolution is not only independent of R (or H) and λ, but also decreases with a decrease in diameter of the antenna D.

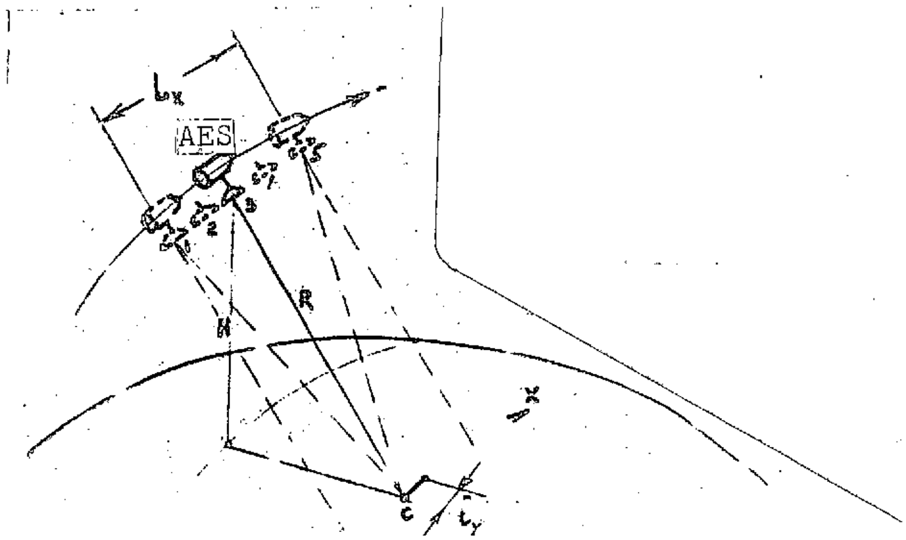


Figure 29

The practical realization of a radar with a synthetic aperture requires memory devices, phase (coherent) processing of the signals, and time stability of the system parameters.

The quadratic dependence of the intensity of the return on D makes it undesirable to decrease the diameter of the antenna, even in radars with synthetic apertures.

The combination of a side looking radar and a synthetic aperture will make it possible to obtain radio images with good resolution. Furthermore,

$$\ell = \frac{c\tau_1}{2}; \quad \ell_x = D,$$

that is, resolution does not depend on the altitude, but is determined by the parameters of the system itself. The processing of the signals to obtain small values of l_x with real values of D may be carried out by other methods. In these methods, one of the coordinates of the surface element and in the side looking radar, as well is determined by the delay ΔT, while the other coordinate is given by the Doppler frequency shift ΔF_D.

To achieve this, the radar beam is directed not only to the side, but also to the front (or to the back) with respect to the vertical. Figure 30 gives the intersection of the beam with the surface. Lines of equal ΔT and equal ΔF_D are drawn on the cross section.

Thus, in this case, each element of the irradiated surface is assigned coordinates (ΔT, ΔF_D), rather than coordinates (x, y).

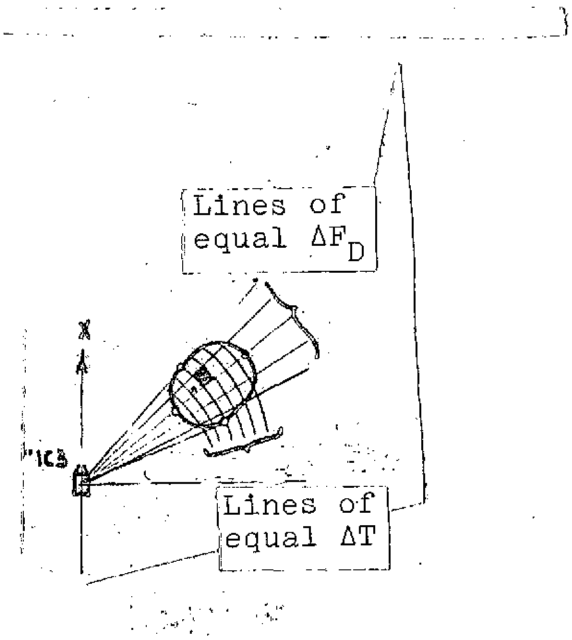
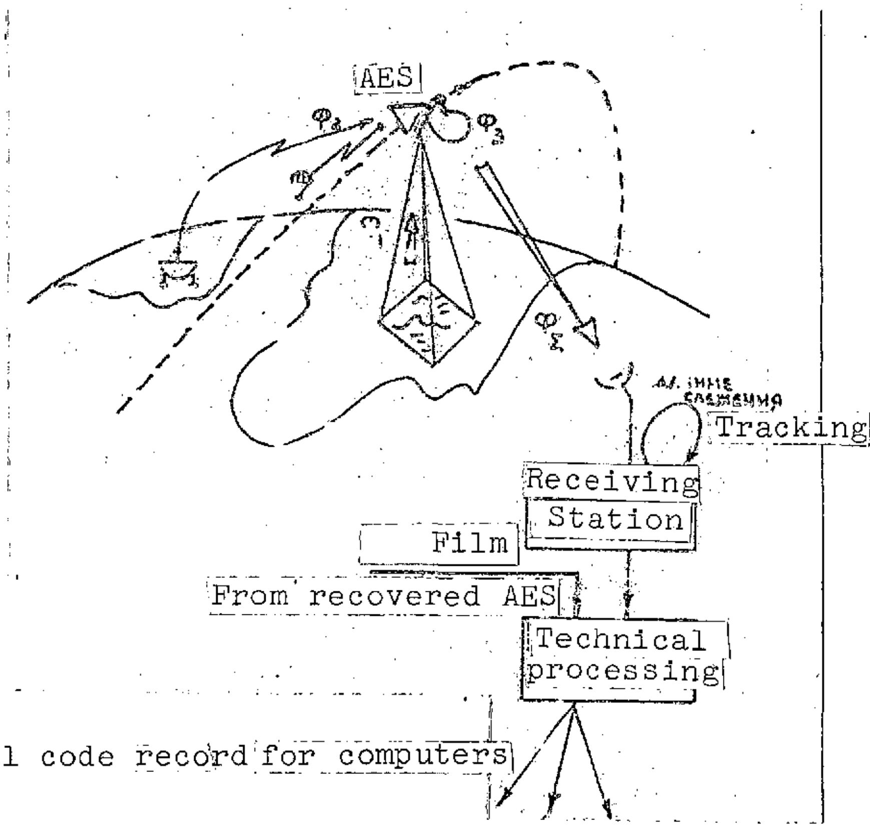


Figure 30

Collection and Transmission of Data

The overwhelming amount of information obtained by remote sensing instrumentation is transmitted from the AES to the receiving ground stations by radio. Furthermore, the locations of the receiving stations may not coincide with the regions and services for which the received information is destined. Therefore, the necessary data processing consistent with the needs of the branch or service may be best carried out directly by the involved services. However, for such processing (let us call it interpretation) to occur, it is first necessary to perform a preliminary technical processing, required by all services. The schematic diagram showing the collection and processing of information is given in Figure 31. /65



1. Video digital code record for computers
2. Films
3. Digital and analog data from radiometers

For interpretational processing

Figure 31

The AES, in addition to remote sensing (flow Φ_1) may also collect information directly from Earth, sea, and air stations on special radiobands (Φ_2). Data from service instrumentation (Φ_3) adds to the flow. The total flow of information (Φ_Σ) is transmitted to the receiving station, whose instrumentation determines additional AES tracking data which is necessary to subsequent processing. All the information is usually recorded on magnetic recorders.

Technical processing may be carried out in centers which are associated with the receiving stations or which are at a distance from them. In the latter case, there must be a special communications or transportation link between the receiving station and the center of technical processing. The results of technical data processing are given in a format convenient for special and interpretational processing.

In examining the operational principle of the television devices and scanning radiometers, we became convinced that they generate a significantly greater number of signals per unit time (perform more measurements) than do any other non-scanning devices. In addition, it was noted that the reading speed of the output signal from the sensitive element in scanning radiometers could not be decreased in comparison with the scanning speed of the surface elements. Therefor, the maximum information delivery rate for given values of the resolution l and swath width L is attained by scanning radiometers. /67

Let us determine the amount of information (more correctly, the number of measurements) delivered by an optical scanning radiometer during 24 hours of uninterrupted operation onboard the satellite.

The AES completes $\frac{24 \text{ hours}}{T_{\text{orbit}}}$ orbits about the Earth per day. It sees a surface:

$$S = L \cdot 2\pi r_0 \frac{24}{T_{\text{orbit}}} \ (\text{m}^2),$$

where r_0 — radius of the Earth, $(r_0 \approx 6370 \cdot 10^3 \text{ m})$,
L — swath width.

If the required resolution on the Earth's surface is l^2 square meters, while the intensity of illumination of each element is determined by the accuracy, required for coding K — binary category code, then N channel scanning radiometers produce a data flow equal to:

$$\Phi_1 = 2\pi r_0 L \frac{24}{T_{\text{orbit}}} \cdot \frac{1}{l^2} \, k N \quad (\text{bits}).$$

For example, let:

$$L = 100 \text{ km}, \quad l = 100 \text{ m}, \quad k = 6,$$
$$N = 4, \quad T = 1.5 \text{ hrs},$$

where /68

$$\Phi_1 = 2\pi \cdot 6370 \cdot 10^3 \cdot 100 \cdot 10^3 \cdot 16 \cdot 10^{-4} \cdot 6 \cdot 4 \approx 1.6 \cdot 10^{11} \ (\text{bits/sec}).$$

This means that the data reception rate from such a device is approximately:

$$C \approx 2 \cdot 10^6 \text{ bits/sec.}$$

A side looking radar with resolution $l \approx 100$ m requires pulse widths of not more than $\tau_{sig} \leq \frac{2l}{c} \approx 0.6$ sec. In coding the intensity level of the return from each element with a six bit code, the data will be received at a rate of nearly 10^7 bits/sec.

The rate of data reception from non-scanning devices, from low resolution devices, as well as from Earth and sea data sources, received over data lines, is smaller by 2 - 4 orders of magnitude than the indicated figures. Therefore, as an approximate estimate, it may be assumed that all the instrumentation onboard an AES (excluding photographic cameras) produce a total data flow at the rate of:

$$C_\Sigma \approx 10^7 \div 10^8 \text{ bits/sec.}$$

Receiving stations "see" the satellite during a limited time period, for example, T_{see} seconds per day. Therefore, data obtained onboard the satellite during the course of a day has to be recorded on magnetic tape for subsequent transmission to Earth during a time T_{see}. This means that with T_{sec} = 15 minutes, it will be necessary to transmit data at the rate of:

$$C_{trans} \approx 10^9 - 10^{10} \text{ bits/sec.}$$

This requires very wideband channels of communications to provide such good signal-noise ratio.

It would be convenient to use a satellite data transmission /69
system for the study of natural resources, such that the time of transmission would not be too small in comparison with the data input time from the AES instrumentation. A possible communication system

could be as follows. Data for the AES investigating natural resources is directly transmitted to ground stations via a space retranslator, located on a geostationary communications satellite. This satellite "sees" the research AES during a considerable fraction of their periods of rotation. For an AES with H = 645 km, it is approximately half of T_{orbit}, while for an AES with H = 6450 km, it is approximately 0.72 T_{orbit}. In turn, the communications satellite is "stationary", and can be seen by nearly all the receiving stations on the Earth's hemisphere.

Taking into account the fact that much of the enormous incoming flow of data to be processed contains operational information, placing constraints on the data reduction time, there is a tendency to automate all laborious processes. This is accomplished by the creation of special devices for the comparison and reduction of data, as well as by use of digital and analog computers.

List of Problems

The state of investigation of natural resources from space /70 requires the solution of a number of methodological, instrumental, technical, and organization problems. In particular, these include:

1. Theoretical and experimental determination of the relationships between the characteristics of natural formations and their remotely sensed parameters.

2. The determination of the recognition characteristics of natural formations and the quantitative determination of their characteristics. The automation of these processes.

3. The development of the methods and algorithms for the calculation of atmospheric effects.

4. The development, in all possible ways, of radio methods and means which are especially necessary for inclement weather conditions. The creation of a light-weight, low-cost radar system with a synthetic aperture.

5. The development of methods and means of investigating subsurface resources from space. The pursuit of an exact determination of the occurrence depth of natural formations.

6. The development of the methodology and means of automatically processing images in order to ensure the timely delivery of information to users. Formulation of data selection and compression methods onboard satellites in order to reduce the flow of measurements transmitted to Earth.

7. The development of principles and methods of immediate signaling of remote sensing of dangerous "natural" phenomena (fires, signs of volcanic activity, anomalous conditions of the atmosphere and the world's waters).

8. The development of principles and means of immediate data transmission from satellites directly to the regions which are end-users of the data. The attainment of the principle of directional transmission of information from the satellite to the requesting smaller ground station.

9. The compilation of catalogs of remotely sensed natural /71
formations and their characteristics (according to their geometric, spectral, evolutional, and other characteristics).

In conclusion, it should be emphasized that the development of methods and means of remote sensing of various media, the automation of recognition processes and of other methods of information processing will have a progressive effect, in our opinion, on the perfection of old, and the creation of new scientific methods (particularly, quantitative and numerical) of investigation in various branches of science and sectors of the economy. It appears, furthermore, that the development of methods and means of investigating Earth formations from space will aid astrophysics in collecting more complete and reliable data in the future on extraterrestrial objects.

Some of the drawings presented in this paper were reproduced from the Proceedings of the International Symposium on Remote Sensing of the Environment, held at the University of Michigan, U.S.A., in 1971.

Translated for National Aeronautics and Space Administration under contract No. NASw 2483, by SCITRAN, P. O. Box 5456, Santa Barbara, California, 93108.